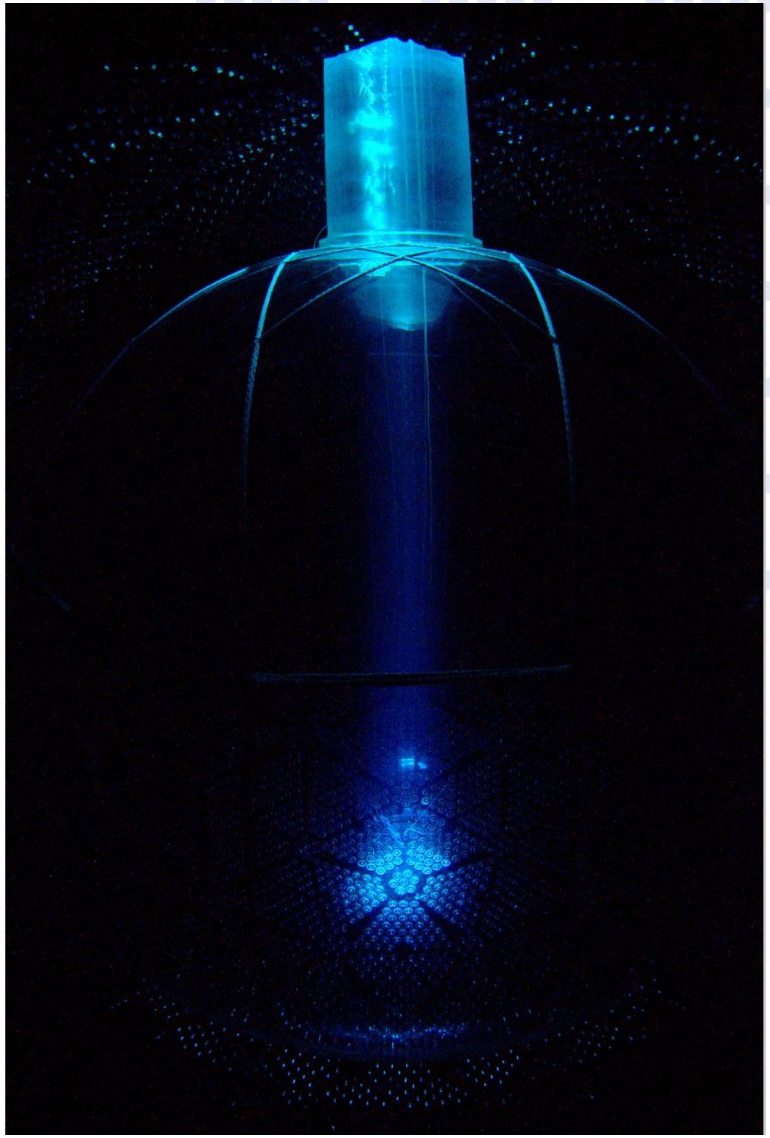
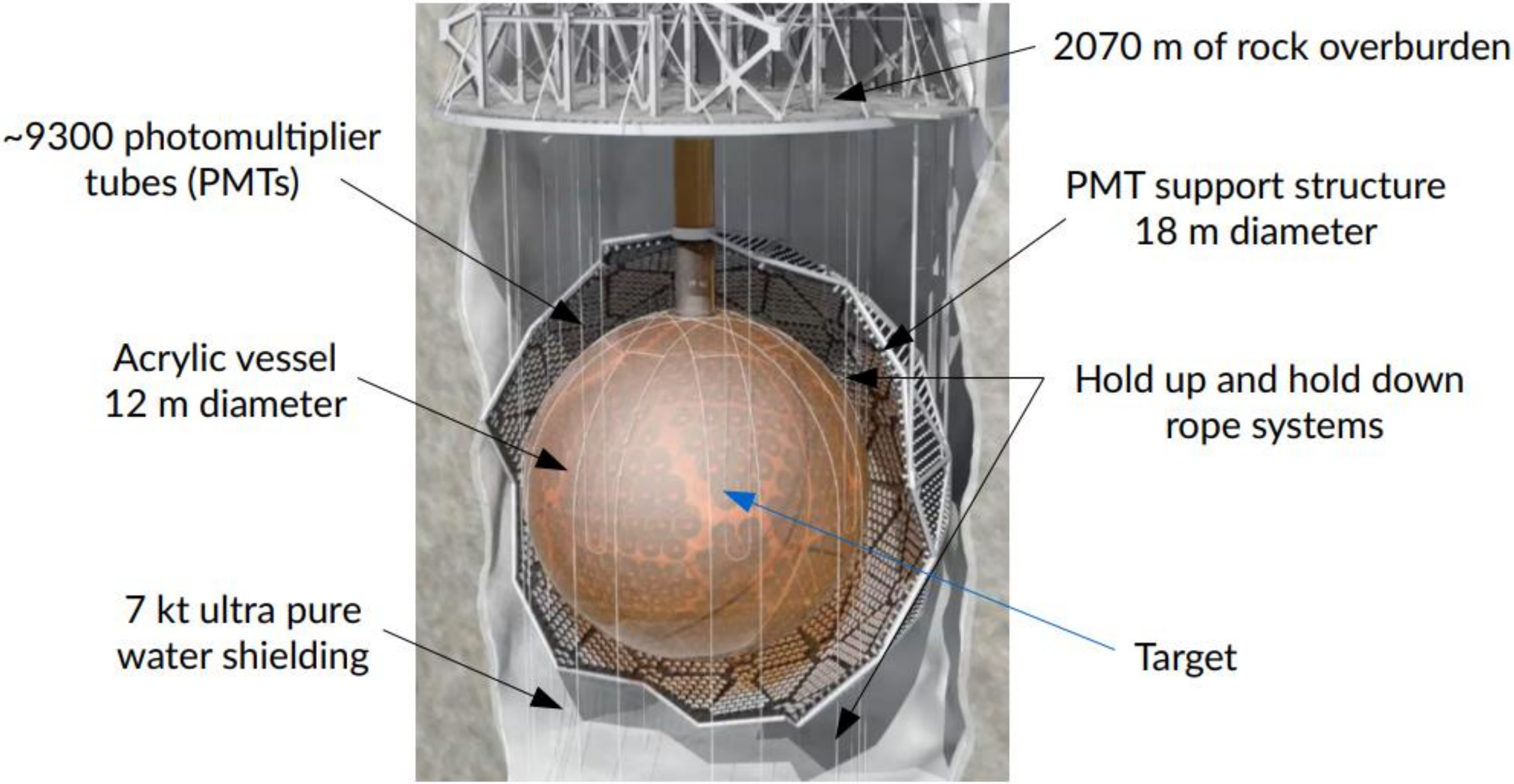
SNO+ Update for SEF

Christine Kraus (she/her) – SNOLAB (Senior Research Scientist)
Adjunct Professor at Laurentian University & Queen's University

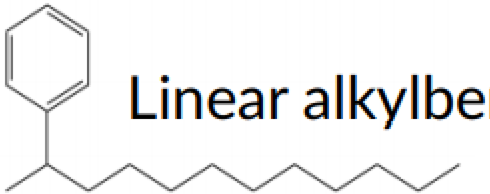
February 4, 2025 SEF - Toronto



SNO+ Detector:
hardware largely inherited from SNO



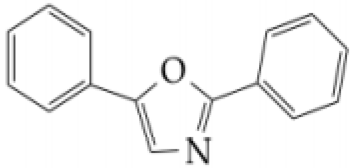
Liquid Scintillator



Linear alkylbenzene (LAB)

+

2,5-diphenyloxazole (PPO)



Measured the scintillator purity in situ

$O(10^{-17})$ g/g for both ^{238}U and ^{232}Th chains

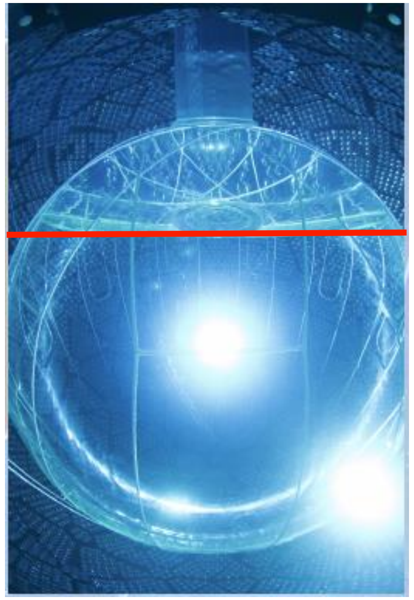
→ *on target for neutrinoless double beta decay search*

"Development, characterization and deployment of the SNO+ liquid scintillator" (JINST 16 P05009, 2021)

SNO+ AV Fill

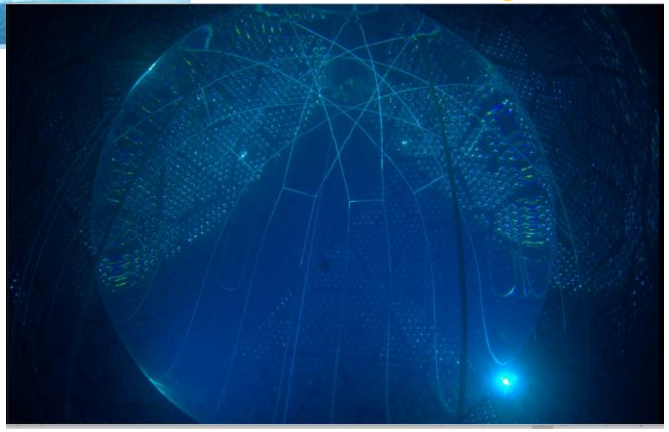
Nov 2018 to June 2019
Commissioning/Early fill
June 2019 to Nov 2019
Background measurement
Dec 2019 to Mar 2020
Fill continued
Mar 2020 to Nov 2020
COVID break → partial fill
Dec 2020 to Apr 2021
Fill continued

~18%



~47% Partial Fill

Apr 2021
FULL!!!
Apr 2022
PPO complete



Recirculation and PPO addition completed Apr 2022

SNO+ Phases and Physics Program

Phases are determined by active detection material in acrylic vessel

Water phase
(May 2017 – October 2019)

- **Nucleon decay**
- **Solar neutrinos**
- **Reactor antineutrinos**
- Supernova neutrinos

Scintillator phase
(April 2021/2022 – 2025?)

- Solar neutrinos
- Reactor antineutrinos
- Geo-antineutrinos
- Supernova neutrinos

Tellurium phase
(2025? –)

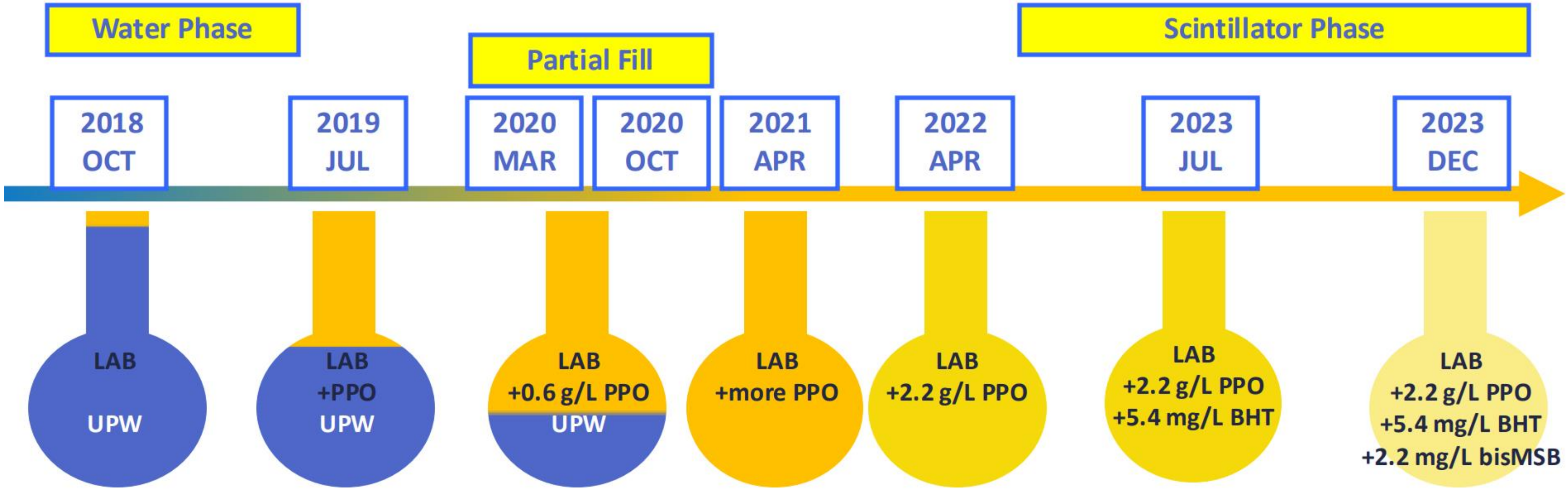
Double Beta Decay
Anti-neutrinos

Bonus: Partial Fill
(March 2020 – October 2020)

365 tonnes of scintillator on top of water (47%)

SNO+ has a broad physics Program.

Scintillator Cocktail

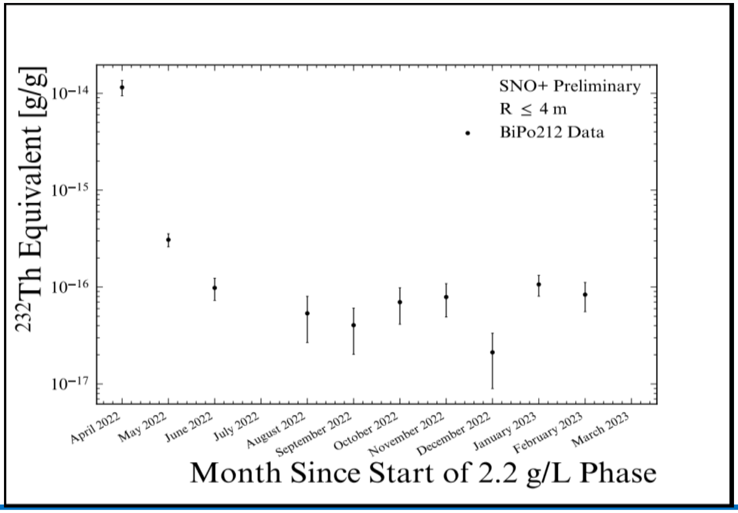


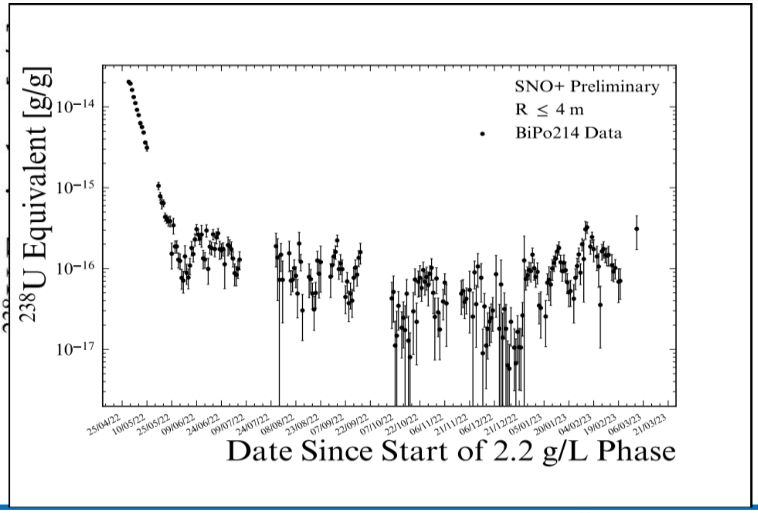
BHT – stabilizer
bisMSB – secondary wavelength shifter (~1.5 x light output)

$^{232}Th = (5.29 \pm 0.762)10^{-17}$ g/g ($^{212}BiPo$)

$^{238}U = (4.32 \pm 0.136)10^{-17}$ g/g ($^{214}BiPo$)

Below target !!





Slide prepared by A. Bialek for LRT

Recent Results

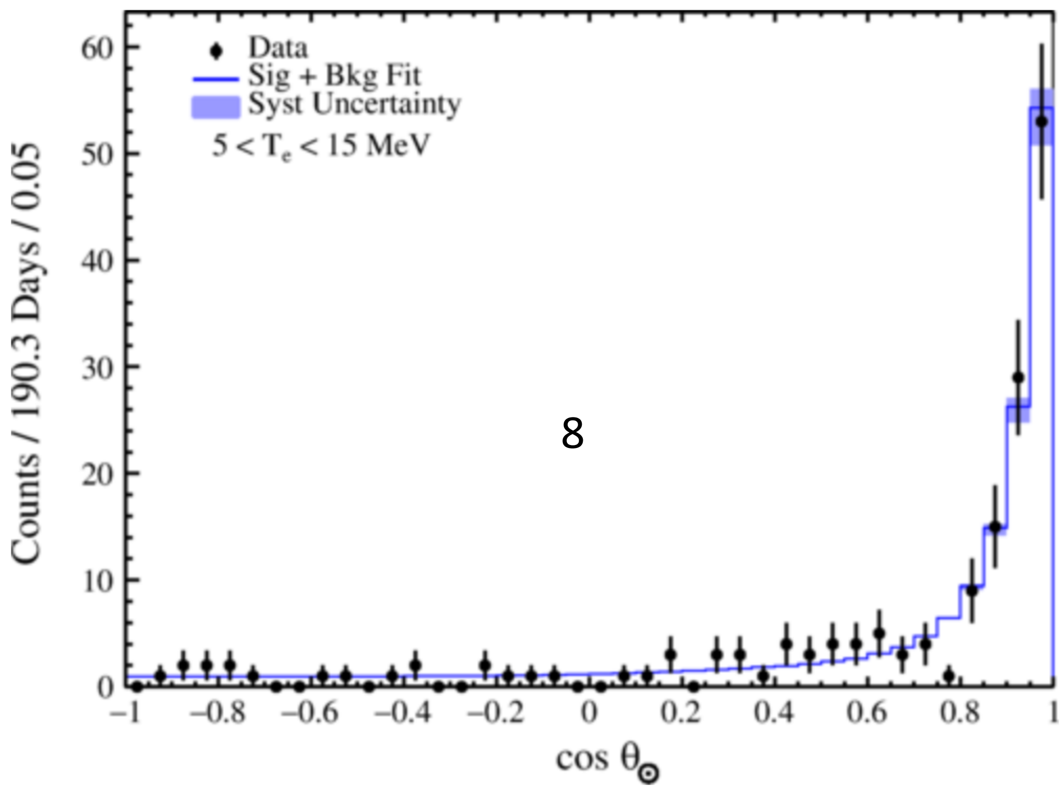
Measurement of the ^{8}B solar neutrino flux using the full SNO+ water phase dataset

A. Allega[1], M. R. Anderson[1], S. Andringa[2], M. Askins[3,4], D. M. Asner[5], D. J. Auty[6], A. Bacon[7], F. Barão[2,9], N. Barros[10,11] *et al.* (SNO+ Collaboration)

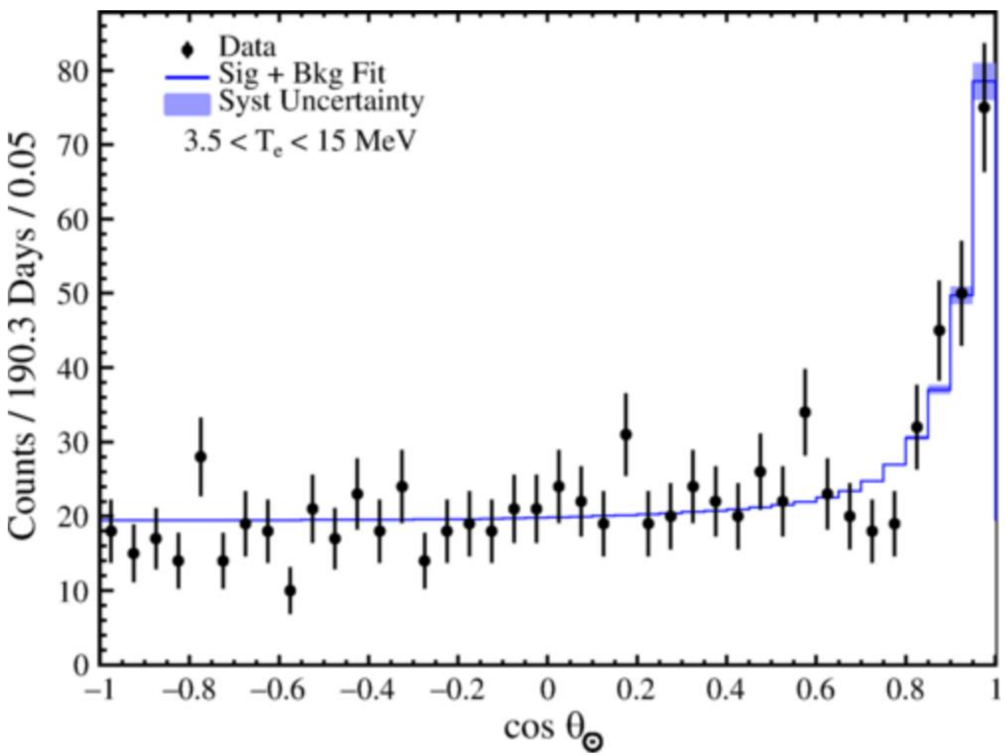
Show more

Phys. Rev. D **110**, 122003 – **Published 16 December, 2024**

Full water phase solar results – 282.4 days data



Angular distribution 5-15 MeV – lowest background rate every measured in water Cherenkov – 0.32 +/- 0.07 events/kt-day



Angular distribution 3.5-15 MeV. Best solar fit result:

$$\left(5.36^{+0.41}_{-0.39}(\text{stat})^{+0.17}_{-0.16}(\text{syst})\right) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}.$$

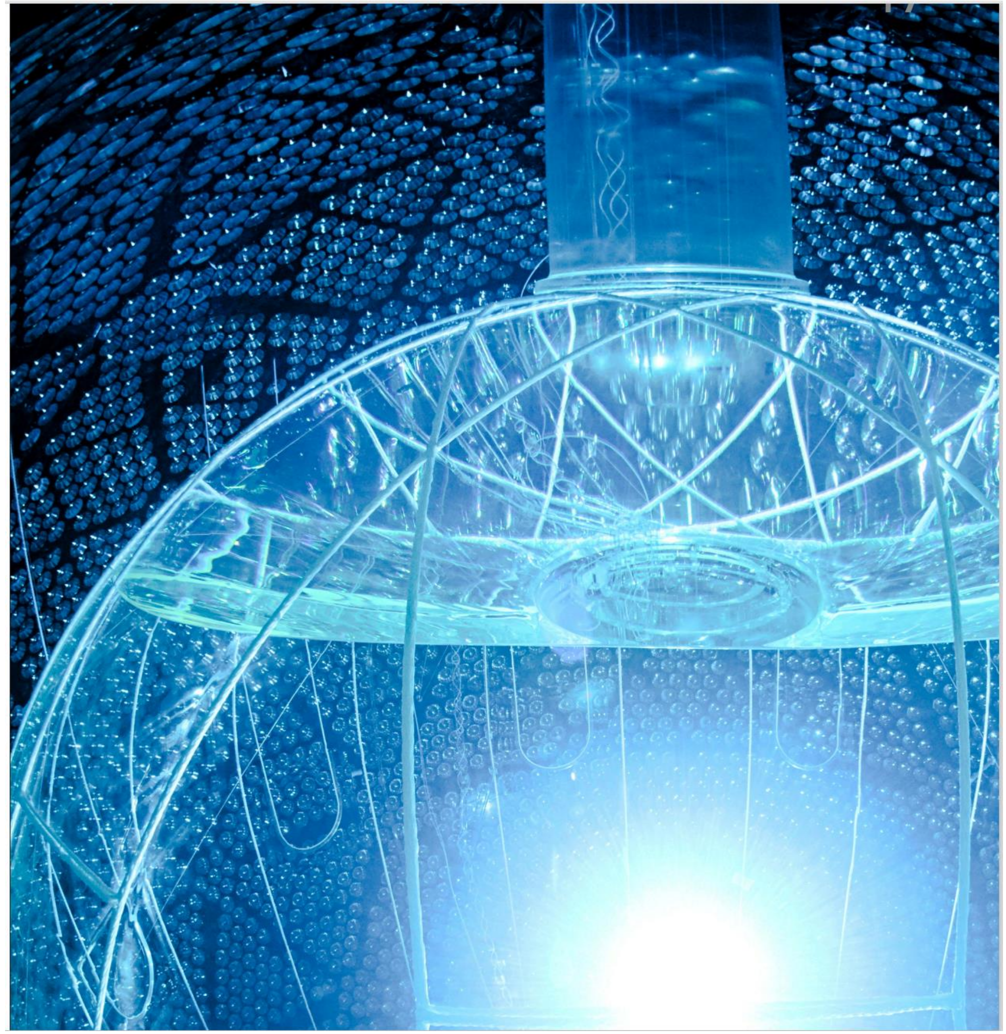
Partial Fill

Unexpected 7 month data set (March to October 2020)
with 370 tonnes LAB and 0.6 g/L PPO (~300 p.e./MeV)

Lower trigger threshold from 1 MeV → 40 keV

- More 8B solar data
- Anti-neutrino data
- Detailed background studies
- External Calibrations

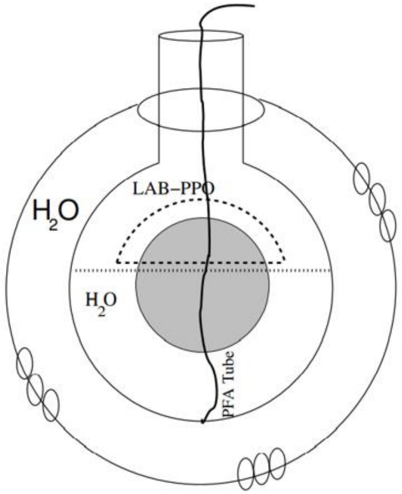
Working on publications …



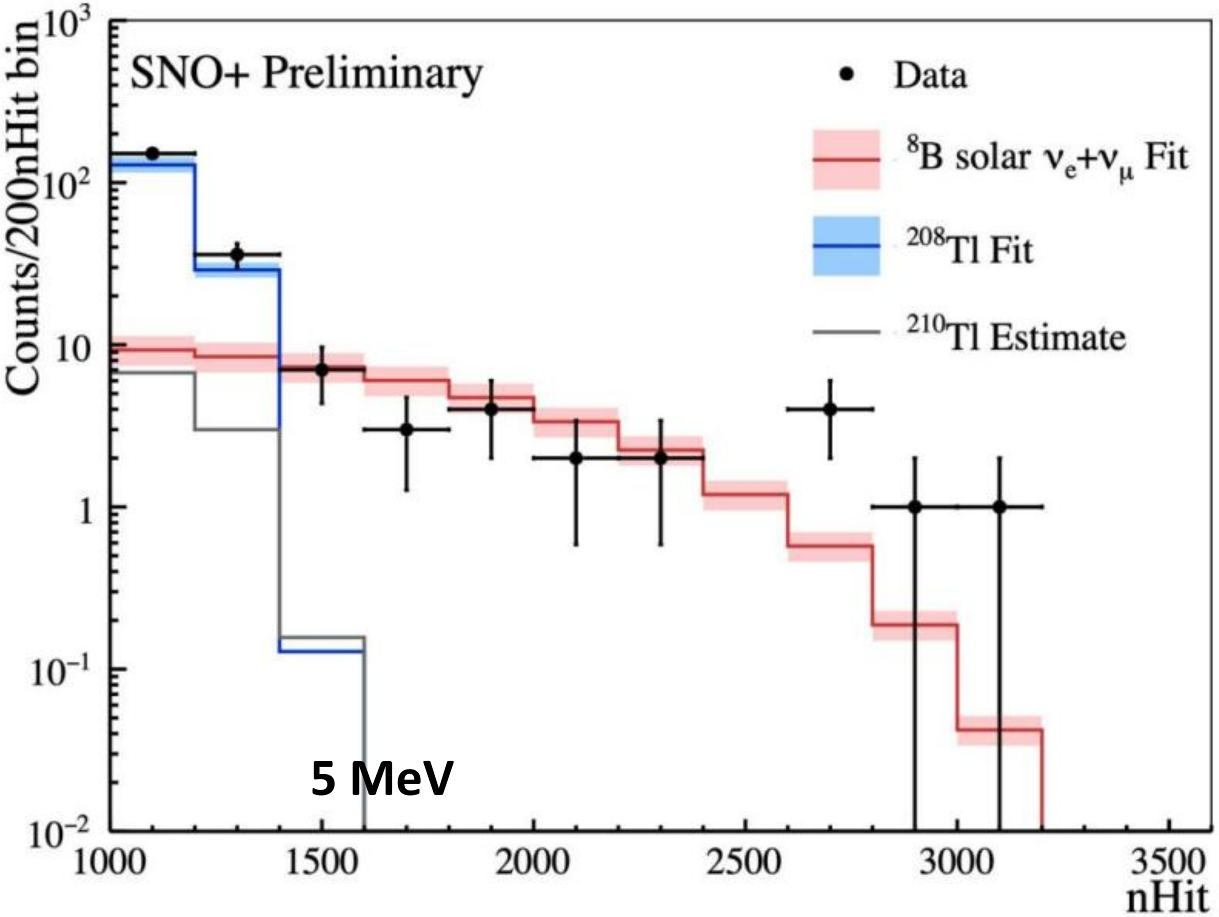
Partial Fill Solar Analysis

Exposure of **92 ton-years** used to measure **^{8}B solar neutrino flux**

Fit ^{8}B (e^- elastic scatters) and radioactive background contributions. Observe **20 events** above 1500 PMT hits (~5 MeV) – consistent with predictions



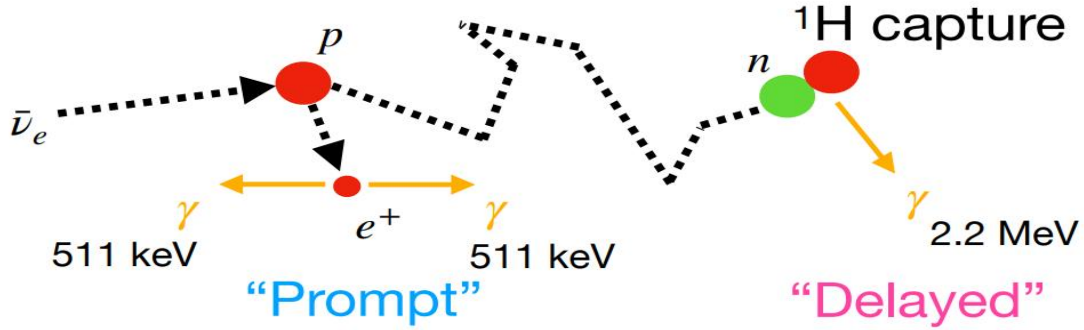
Demonstrates SNO+ liquid scintillator solar detection. *Conditions sub-optimal*



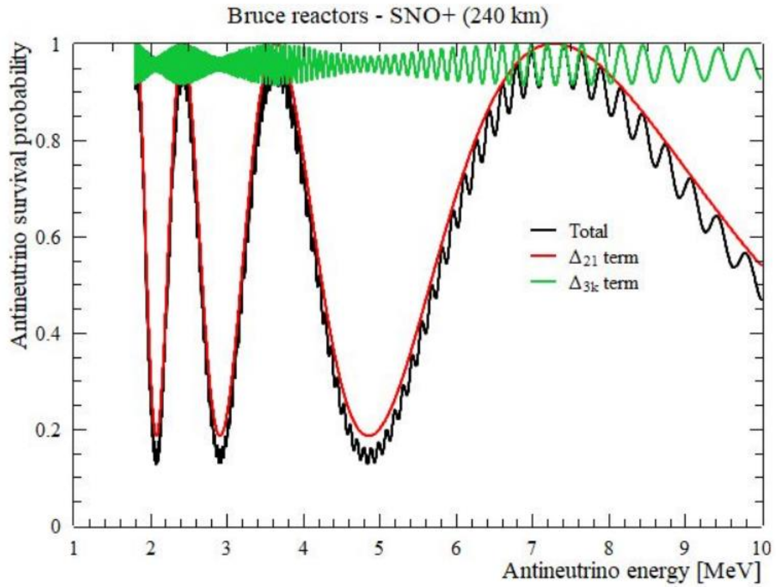
Proxy for Energy

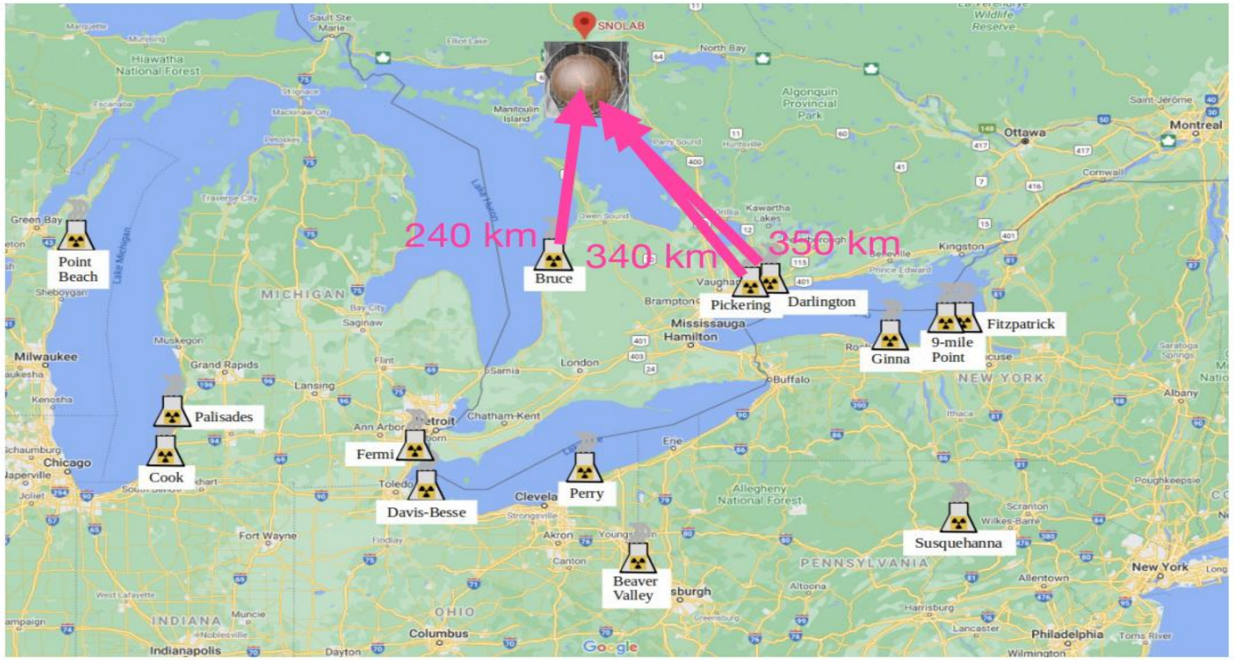
Reactor Anti-neutrinos via Inverse Beta Decay (IBD)

IBD: $\nu_e + p \rightarrow e^+ + n$ anti-neutrino scatters off proton producing positron and neutron



Survival probability vs. energy



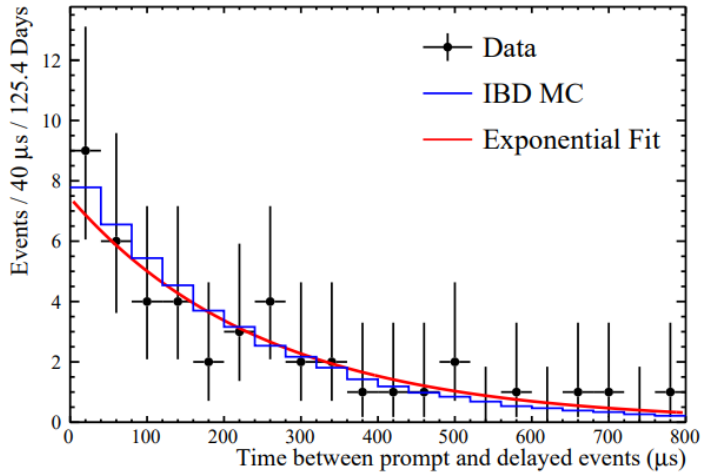


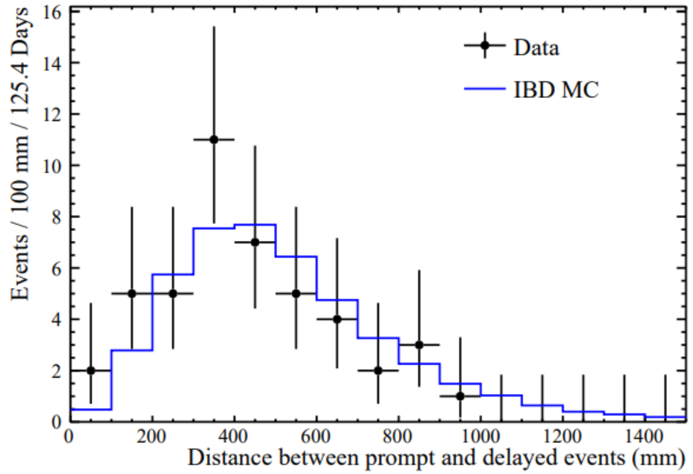
- Canadian reactors Bruce (39%) and Darlington/Pickering (18%) contribute most of the total flux for SNO+
- This measurement constraints oscillation parameters and preserves Canadian reactor signal
- Neutron source (AmBe) was deployed and demonstrated a neutron detection efficiency of about 50%

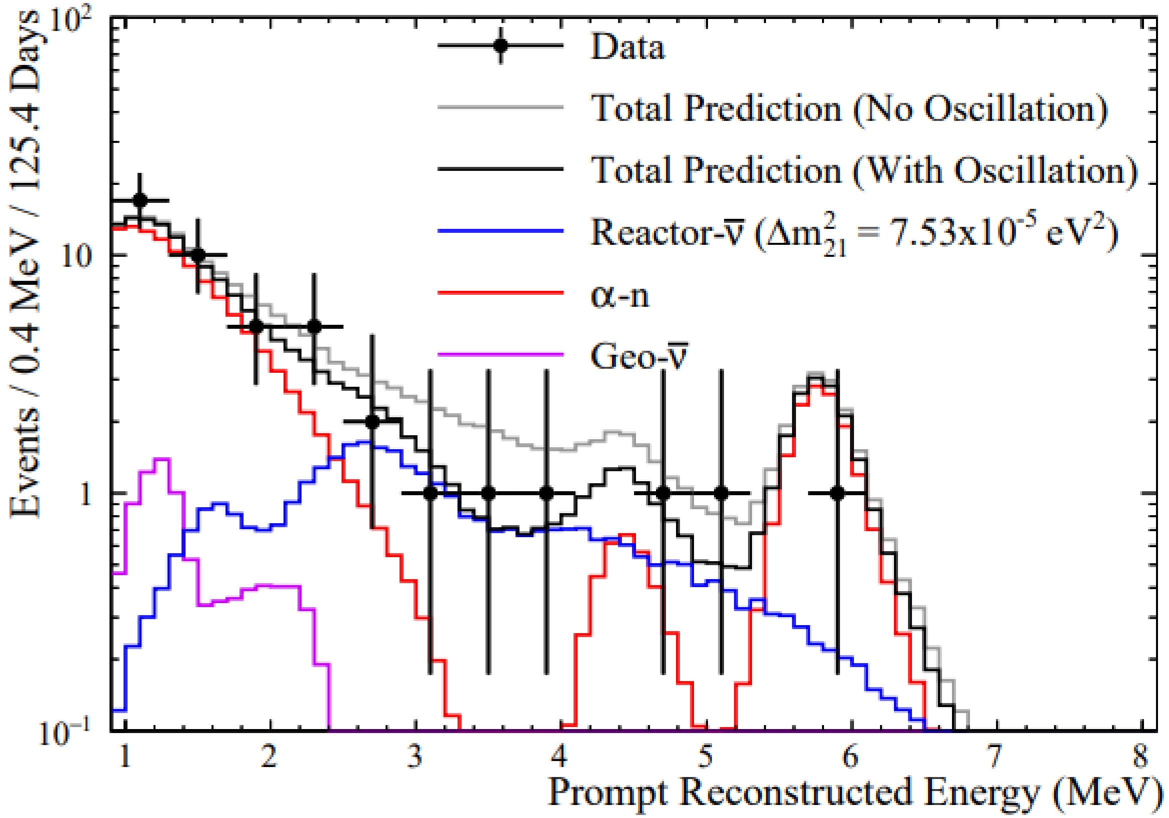
Partial Fill – antineutrino results

Initial measurement of reactor antineutrino oscillation at SNO+

arXiv:2405.19700v2 [hep-ex] 10 Jan 2025







125.4 days,

320t LAB

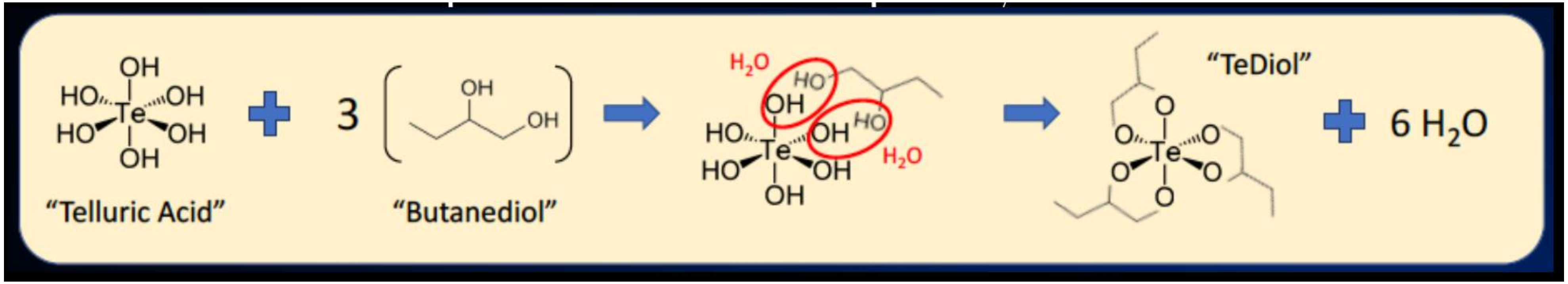
0.6g/L PPO

Mar-Oct 2020

Full Fill analysis Advanced, To be published soon

Double Beta Decay Phase:
load scintillator with Tellurium, 34% isotope ^{130}Te (Q=2.528MeV)

- Form organometallic compound from telluric acid and butandiol -> transparent, soluble in LAB and stable over many years
- Long $2\nu\beta\beta$ half-life (7.0×10^{20} yrs)
- Expect ~400 p.e./MeV for 0.5% loading (amount stored underground)



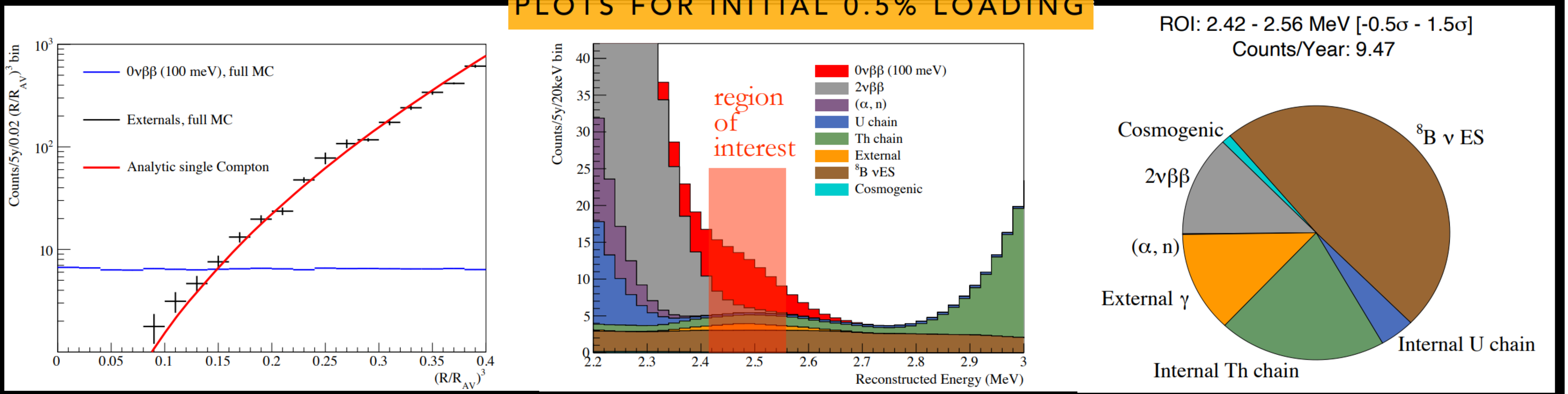
LAB + 2.2 g/L PPO + 2.2 mg/L bisMSB + 5.4 mg/L BHT + TeBD (0.5%) + DDA (0.2%)

“Dimethyldodecylamine” as stabilizer (amine)

Sensitivity Double Beta Decay

Slide from J. Maneira – NNN24 talk

PLOTS FOR INITIAL 0.5% LOADING

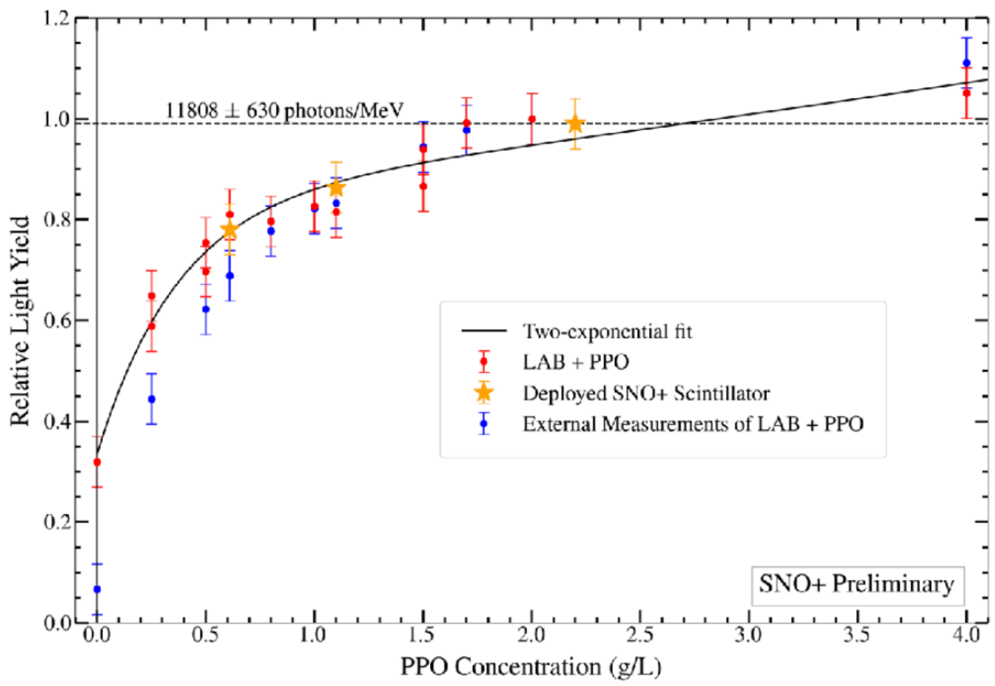


- Water phase constrained external backgrounds
- Scintillator phase constrained several internal backgrounds
- Other expectations based **conservatively** on raw purity and purification factors

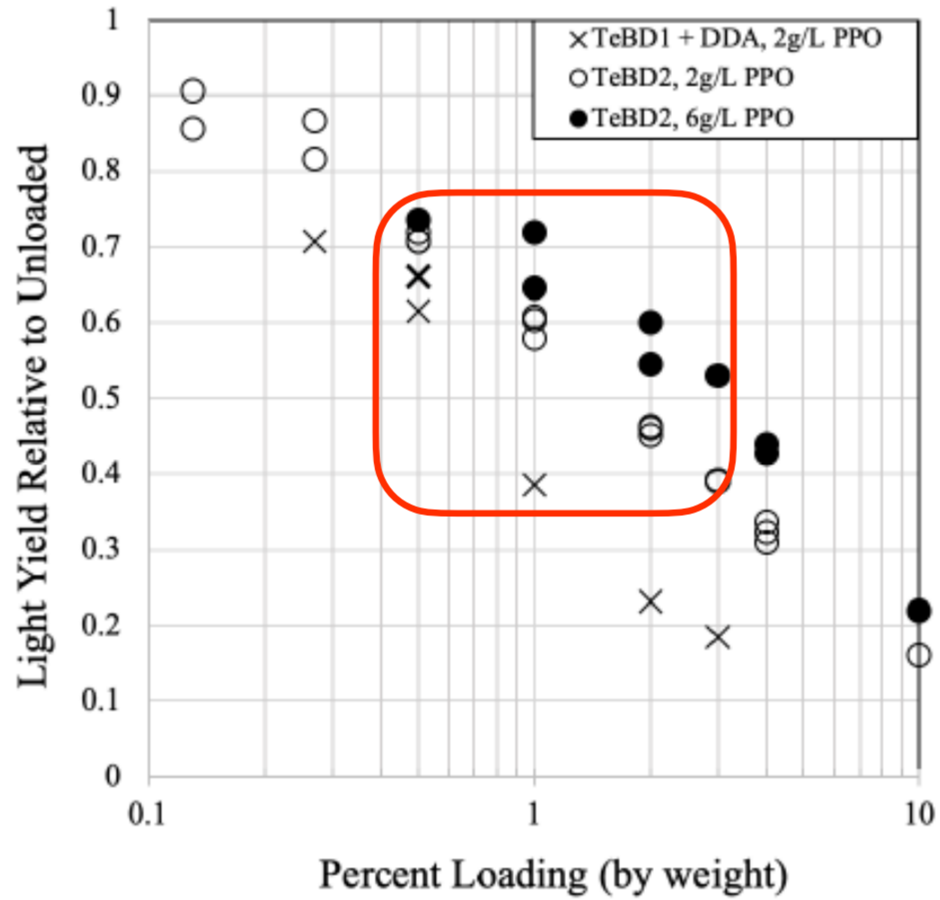
INITIAL 0.5% LOADING: $T_{1/2} > 2 \times 10^{26}$ YRS, 90% C.L., 3 YRS

FUTURE 1.5% LOADING: $T_{1/2} > 7.4 \times 10^{26}$ YRS, 90% C.L., 5 YRS

Light Yield for higher Loading

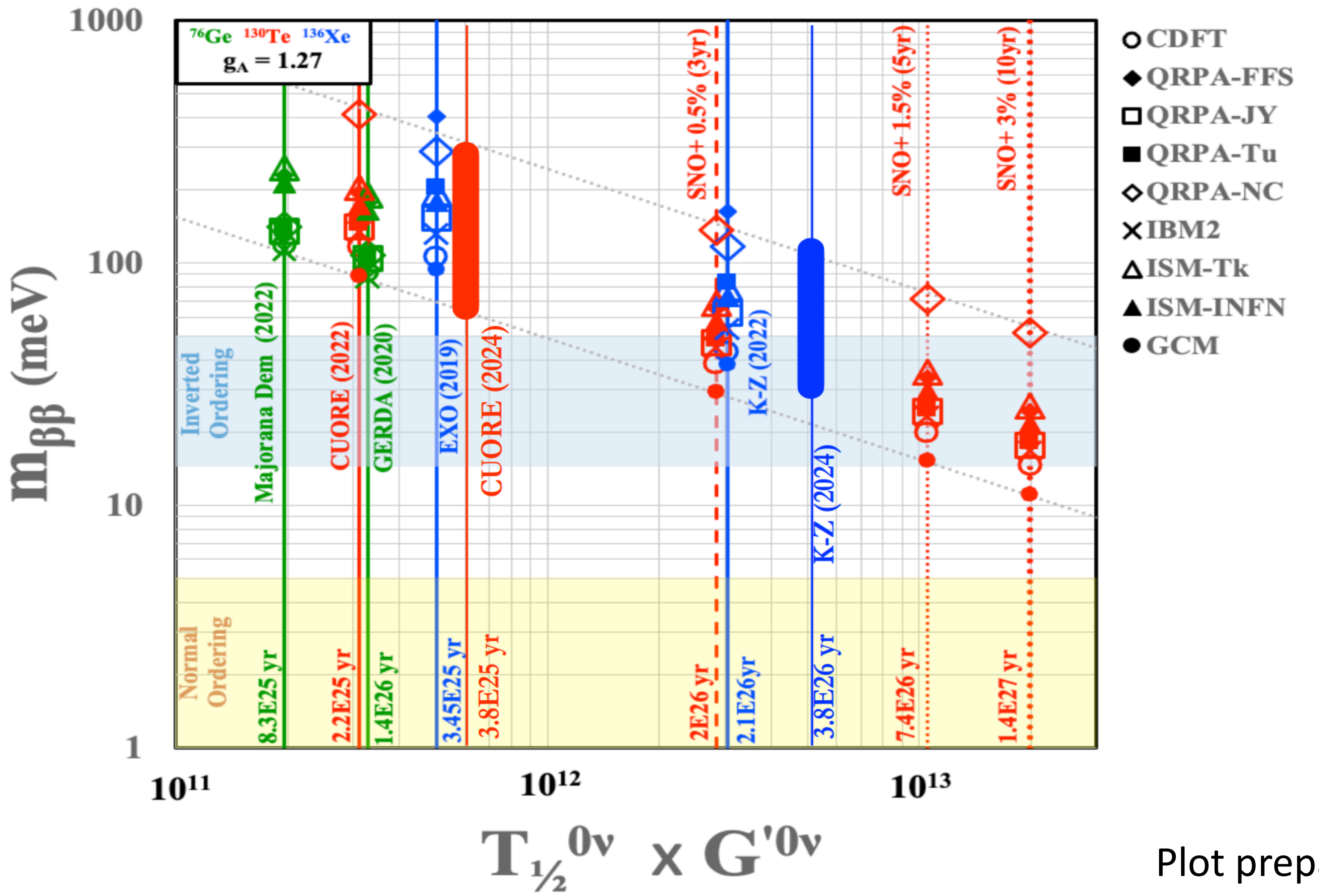


Light yield (LY) measured in SNO+ detector with increasing PPO levels



LY can reach 60% of unloaded LS, even at 2% loading

SNO+ in context



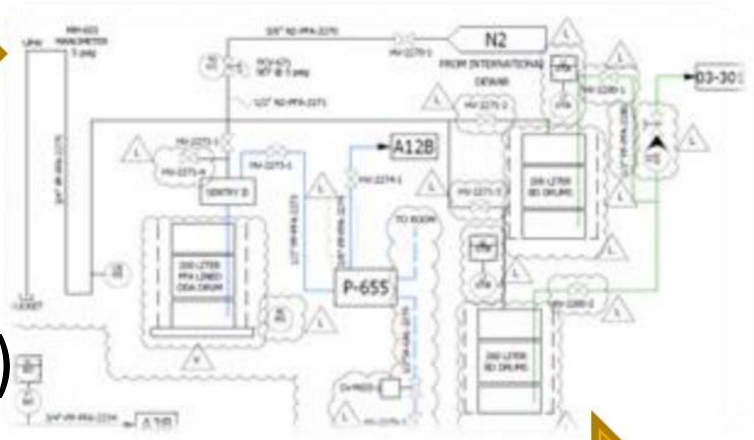
Plot prepared by S. Biller

Tellurium Systems

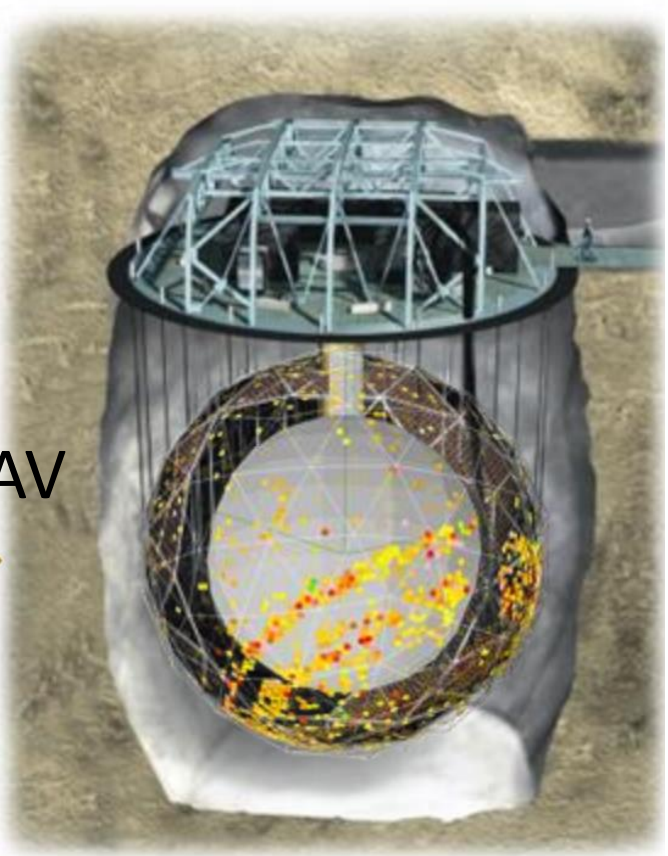
Transport UG, then transfer

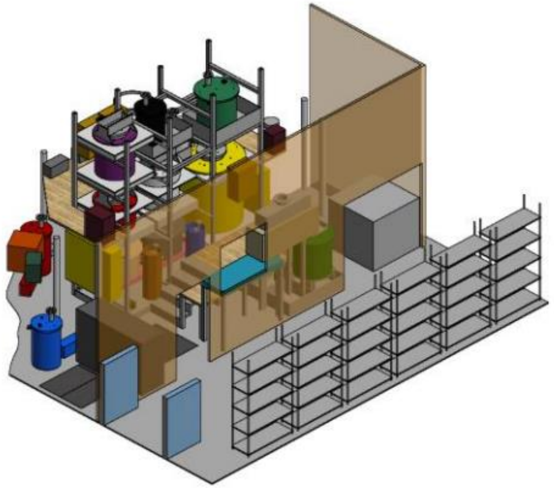
BD purification in scint plant

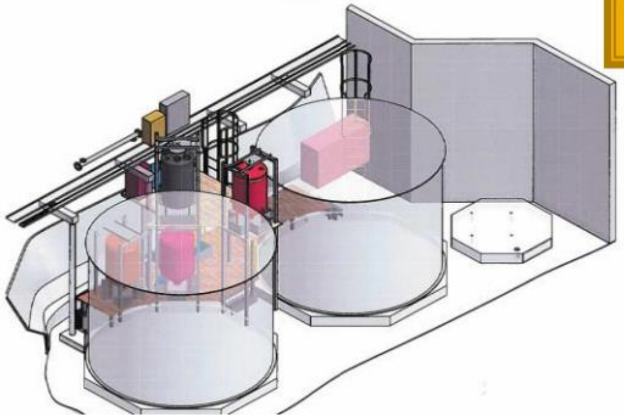
DDA Distillation (surface)



Transfer to AV







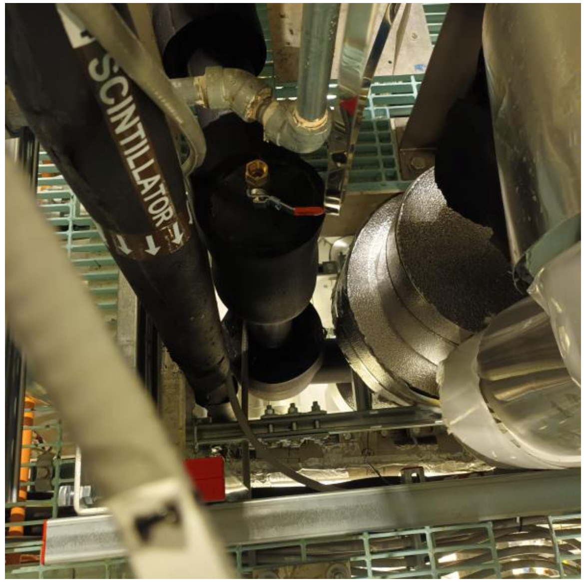
TeA – test batch 2024

Diol plant – test batch later this year

Scintillator Plant – BD distillation

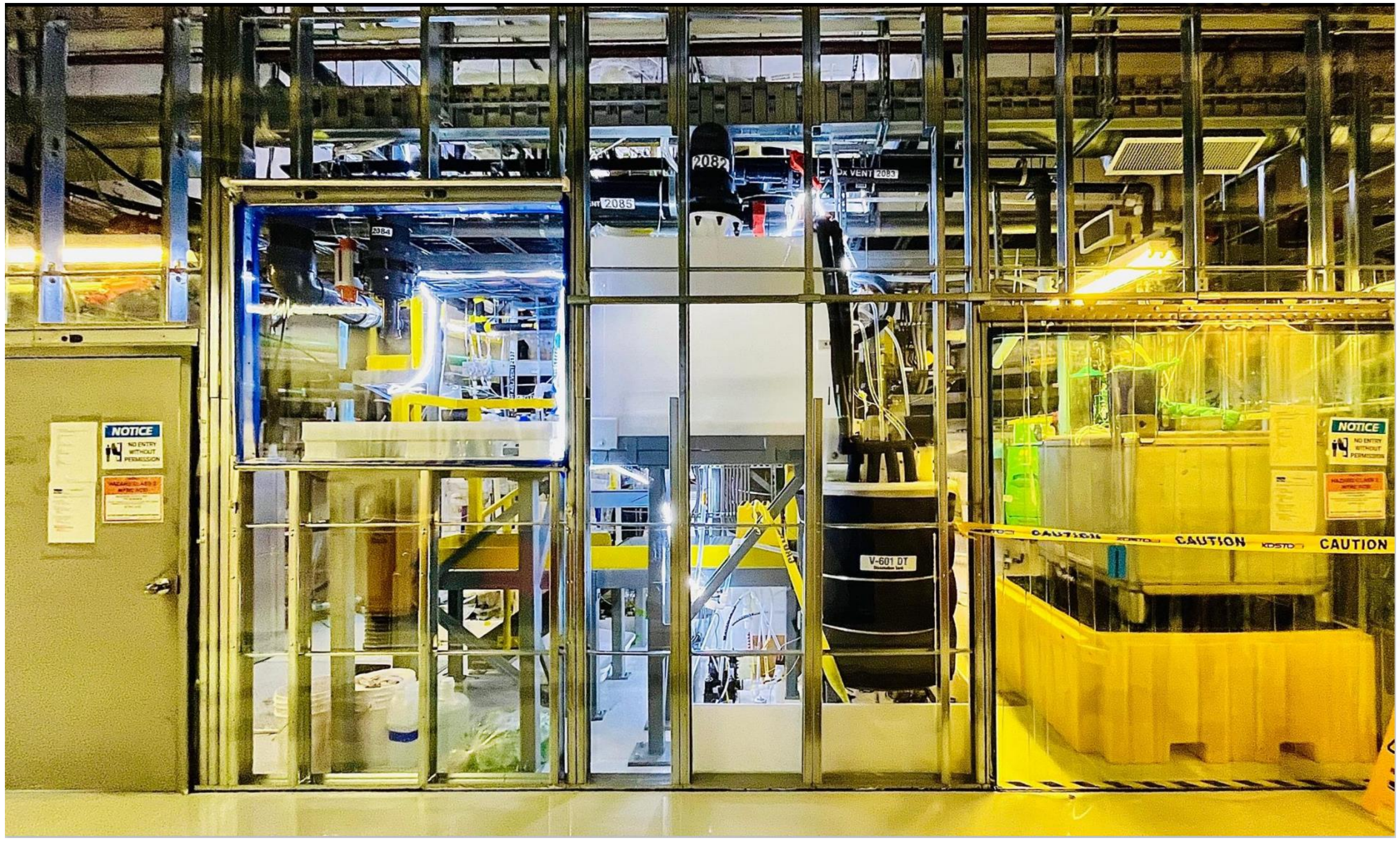
- New hear exchanger E104B successfully installed and tested in December – looking great – faster startup time and higher throughput
- Recommissioning primary distillation after C100 has been cleaned (work ongoing now).
- Distill LAB from drum → as with BD

- BD Commissioning, getting ready for TeDiol, complete transfer stations (first half of 2025)



TeA and Diol Plants - UG

Telluric acid purification



Te-diol synthesis

Actively commissioning

TeA – testbatch – looking good

- Main Goals: Safety (transport and handling of nitric acid and telluric acid sampling
- Process: Plan performance – mechanically, electrical, instrumentation, yields and efficiencies
- Physics (Process Purification QA) – purification factors and ICP-MS analysis

Nitric acid shipping (Mar 10, 2024)

Nitric acid handling UG

Moving drums (7 drums)

Product in glovebox

Sampling

DDA Still – Surface - Commissioning

Located in surface cleanlab

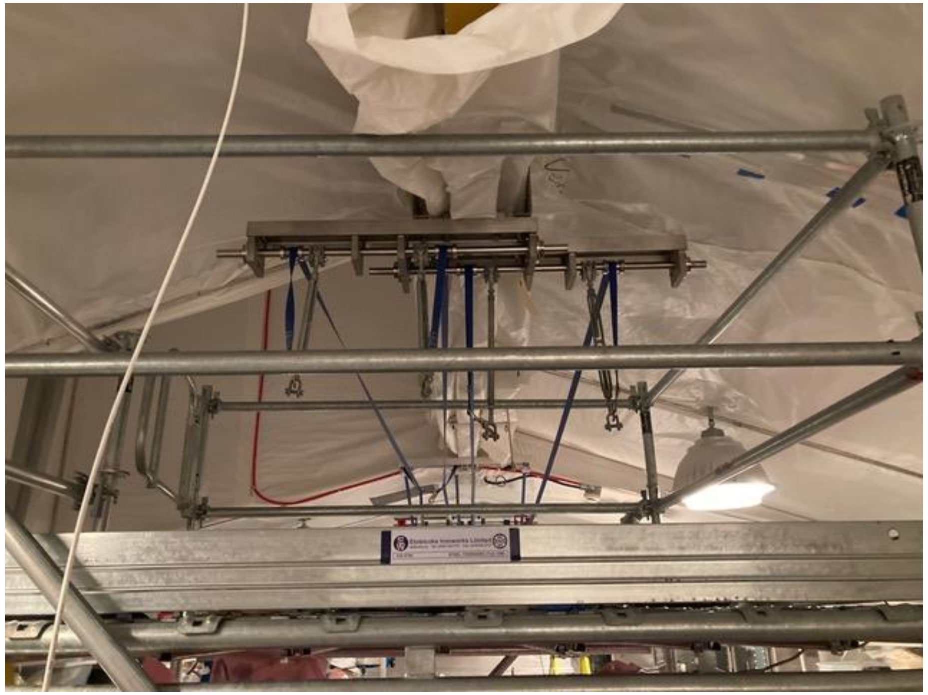
Commissioning with Pope (manufacturer) Q4 2024.

DDA Still commissioning achieved design parameters

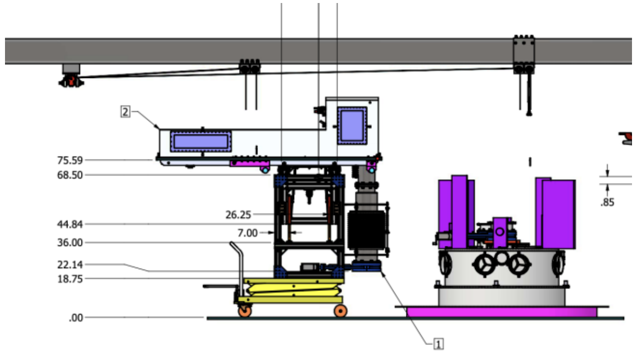
Left: first distilled product
Bottom: QA samples stored away from light and under nitrogen for testing

Calibration Hardware for scintillator phase

URM lifting table

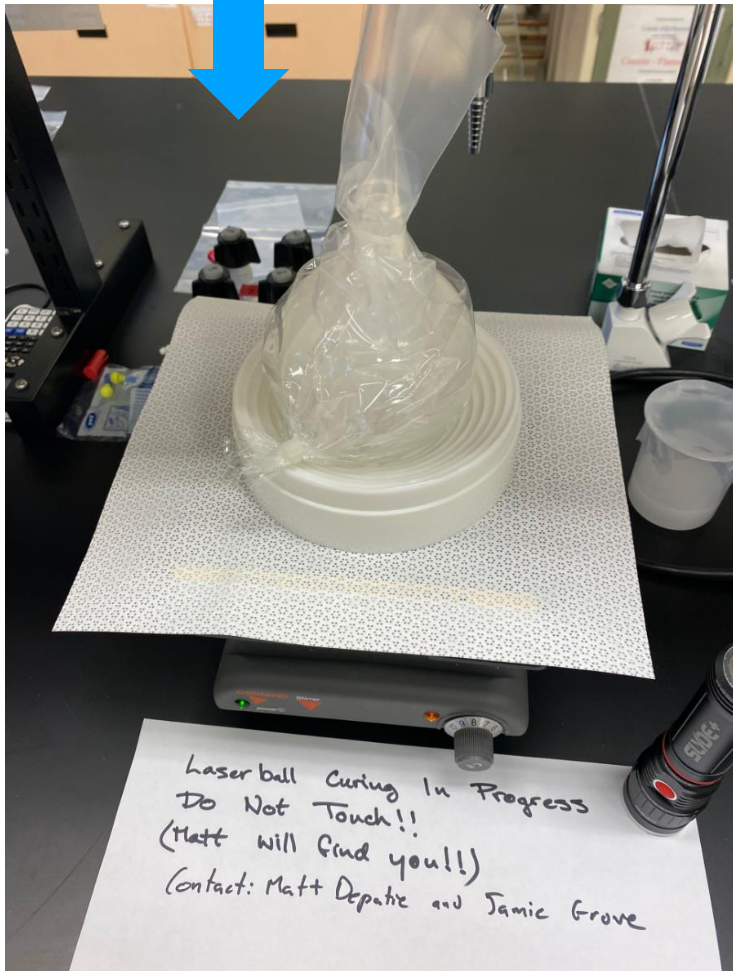


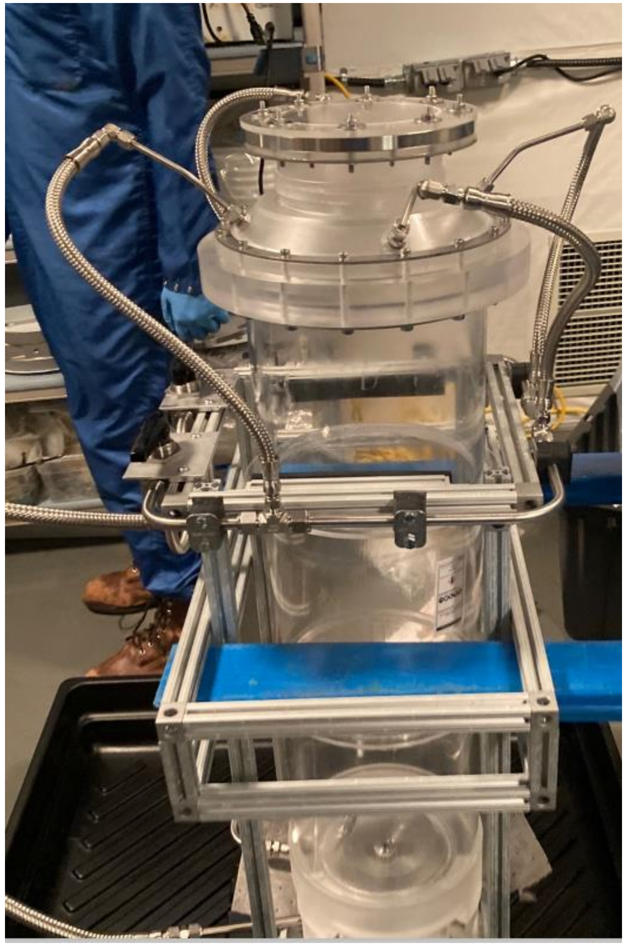
URM hangers



Calibration deployment hardware complete

New Laserball – filled at SNOLAB

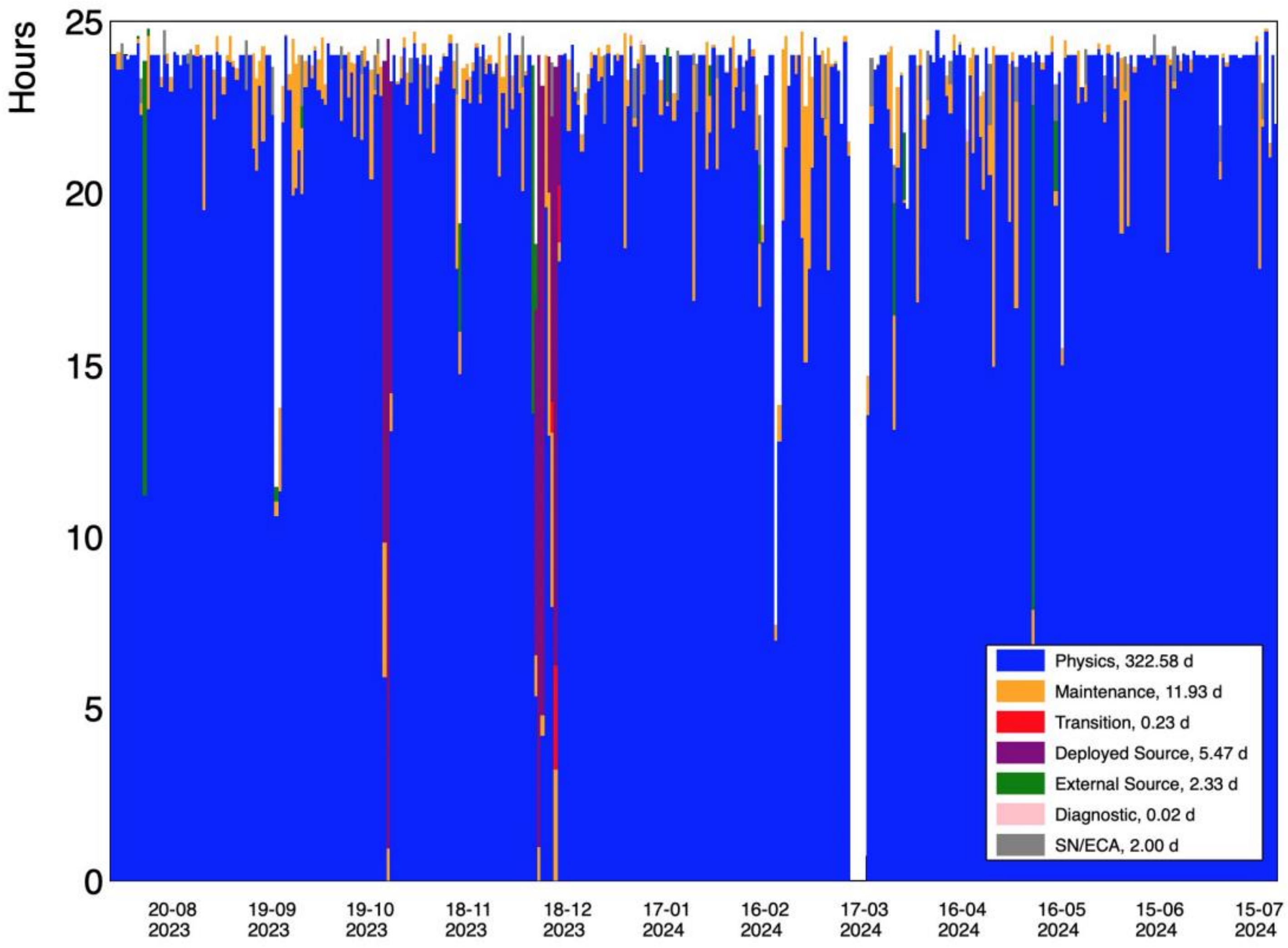




Source Cleaning Vessel

Umbilical

Detector running well – Scintillator Phase



322.58 days uptime – 90.87% in 2023/2024

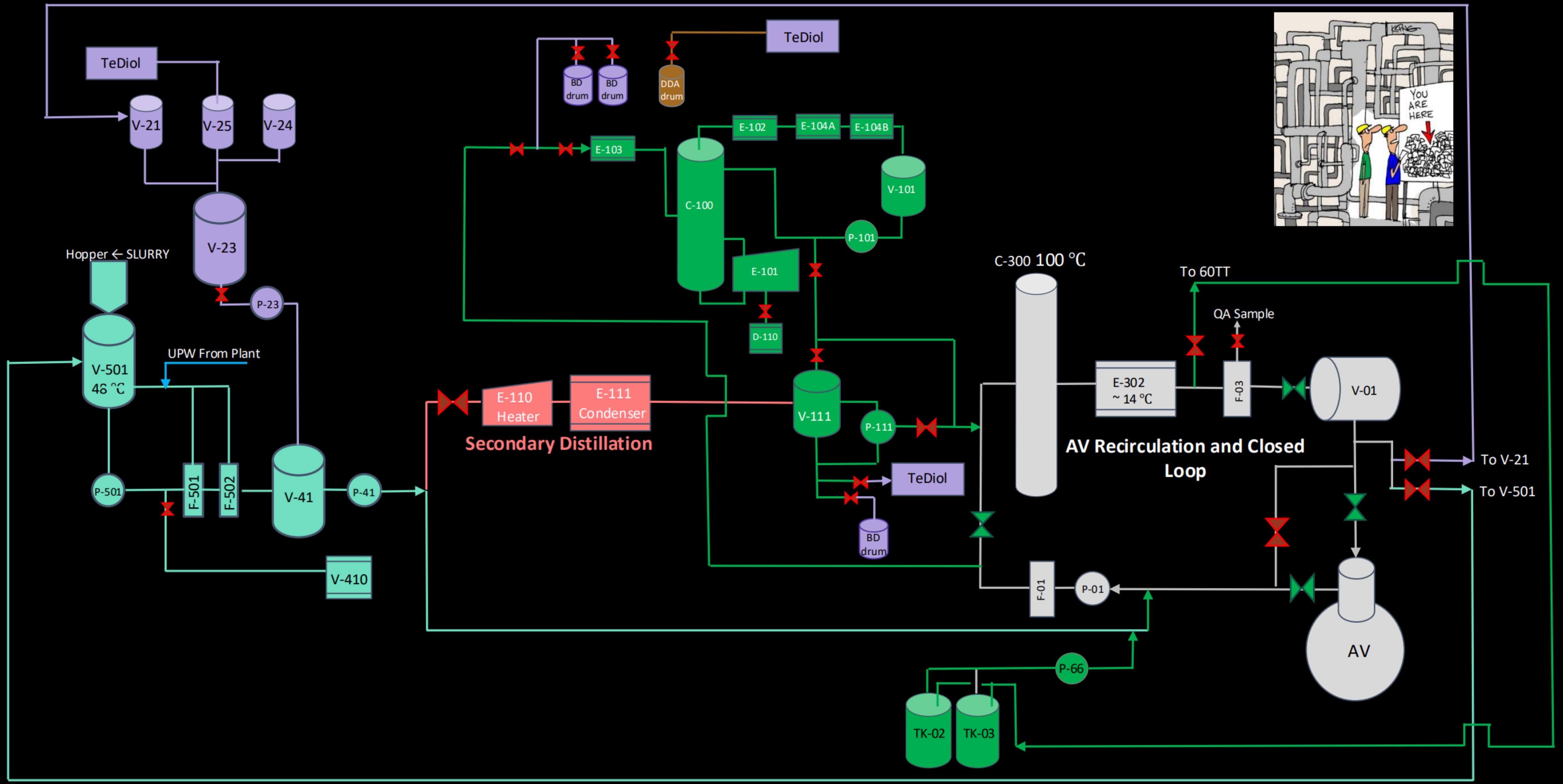
SNO+ Collaboration

SNOLAB

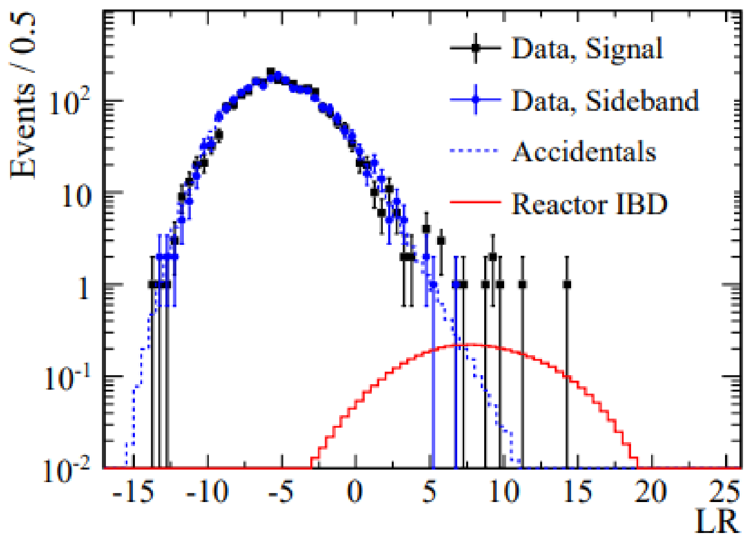
Canada
US
UK
Portugal
China
Mexico
Germany

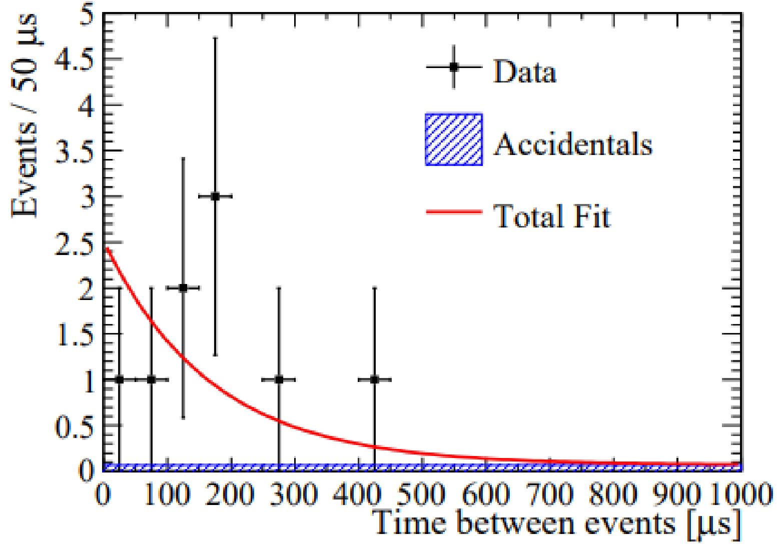
EXTRAS …

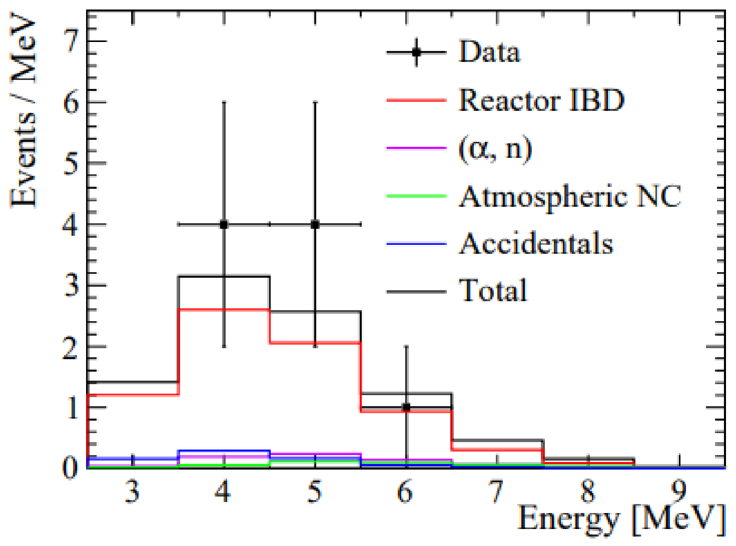
What flows where…



Anti-neutrinos Water Phase - Published







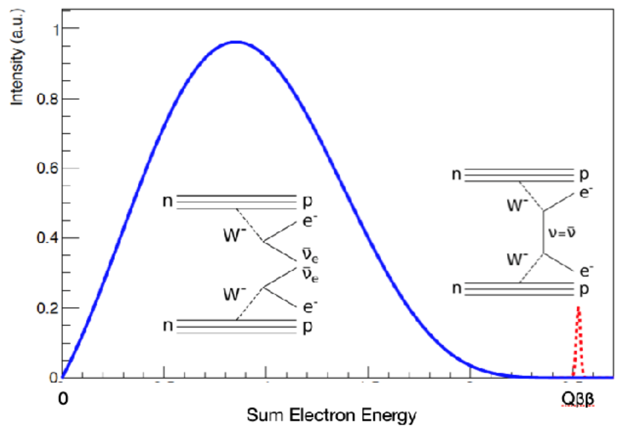
3σ significance – events observed. Nuclear experiment.
arXiv:2210.14154v2 [nucl-ex] 27 Oct 2022 accepted.

Received a lot of media attention !!!

Search for Neutrinoless Double Beta Decay:
the door to the nature of neutrinos and BSM

0νββ

Discovery of 0νββ would be BSM:
Majorana ν & lepton number violation



G. Fantini, ICHEP 2022

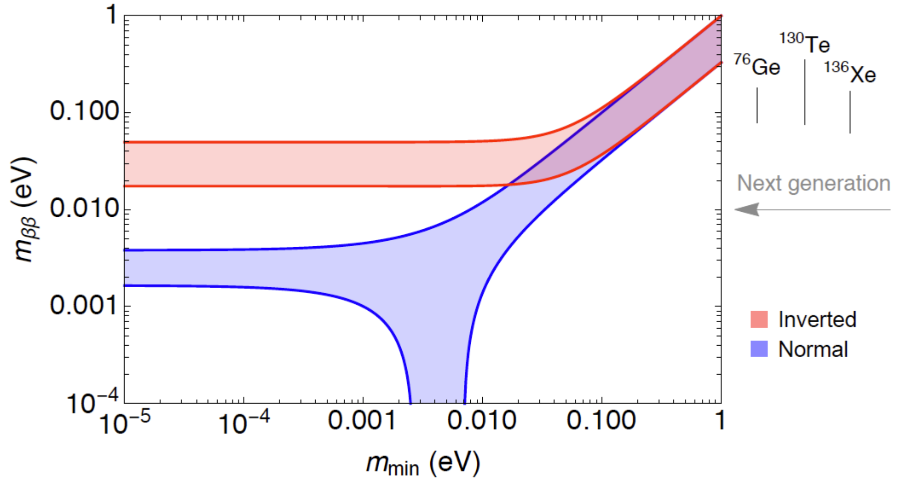
$$\Gamma^{0\nu} = G_{0\nu}(Q,Z) \cdot |M_{0\nu}(A,Z)|^2 \cdot m_{\beta\beta}^2$$

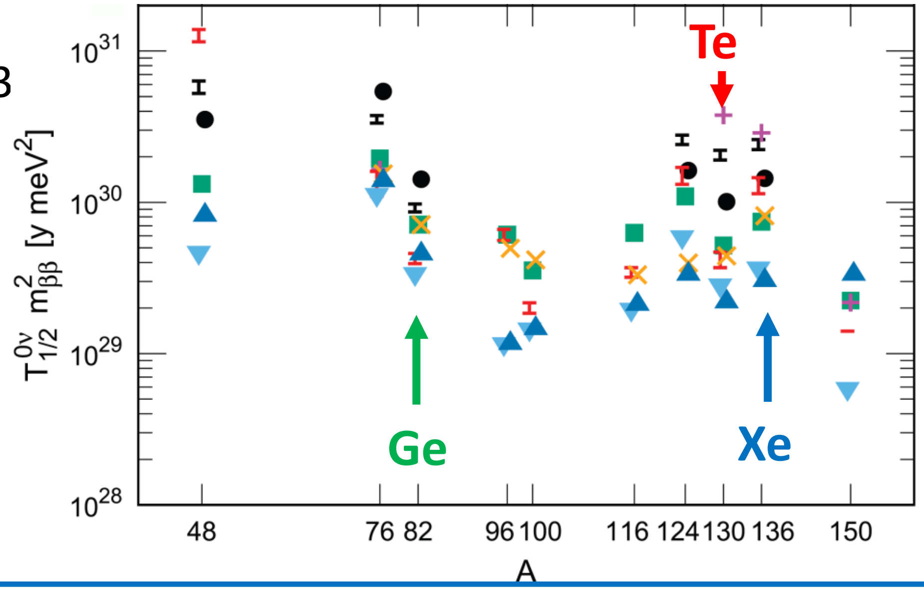
Exp. sensitivity:

$$T_{1/2}^{0\nu} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{for bg B} = 0 \\ a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for bg B} > 0 \end{cases}$$

Nuclear matrix elements;
$M_{0\nu}(A,Z)$ uncertainty: factor 2-3
here shown is $1/(G_{0\nu} \cdot |M_{0\nu}|^2)$

Disclaimer:
$m_{\beta\beta}$ limits are valid only, if 0νββ dominantly via ν exchange





SNO+ Goal: Neutrinoless Double Beta Decay

And the relationship with half-life for $0\nu\beta\beta$ decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

^{130}Te & ^{136}Xe have the smallest $2\nu\beta\beta/0\nu\beta\beta$ ratio