Neutrinoless Double Beta Decay and the SNO+ Experiment

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on behalf of the SNO+ Collaboration

SNO+

Penn
University of Pennsylvania

The SNO+ Experiment

2070 m rock overburden

Multi-purpose neutrino detector
at SNOLAB, Sudbury, Canada

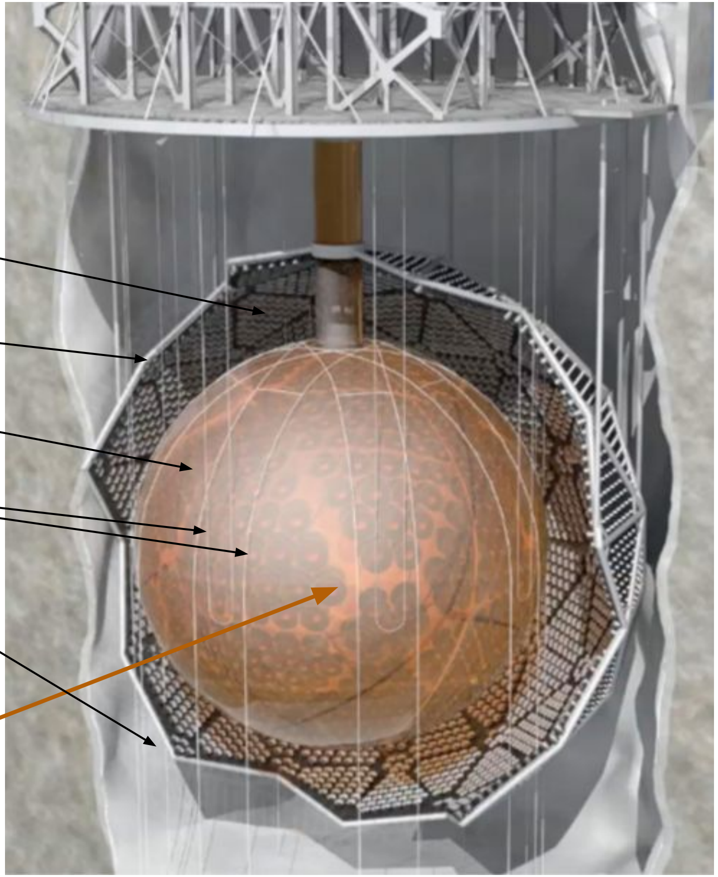
~9300 photomultiplier tubes (PMTs)

PMT support structure, 18m diameter

Acrylic vessel, 12 m diameter

Hold up and hold down ropes

7 kt ultra-pure water shielding



Target

Water phase: **905 t ultra-pure water**
Unloaded scintillator phase: **780 t liquid scintillator** (LS)
Tellurium phase: **4 t of natural Te** loaded to the LS

The SNO+ Experiment

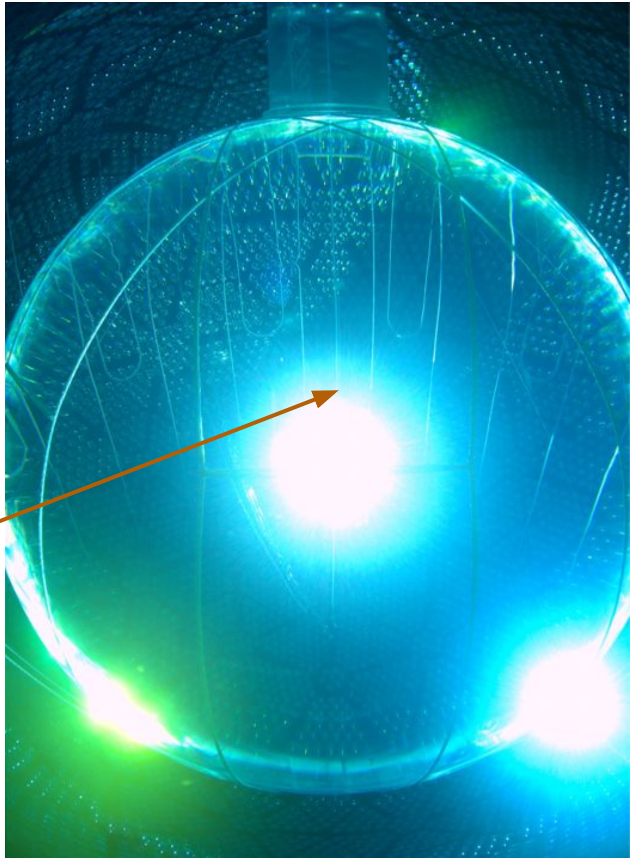
Multi-purpose neutrino detector
at SNOLAB, Sudbury, Canada

Water phase: 905 t ultra-pure water
- *detector calibration and external background measurements*
- *solar neutrino, invisible nucleon decay, n-p capture*

Partial-fill phase: paused filling at 370 t LS due to COVID-19
- *measurement of scintillator backgrounds*
- *reactor neutrinos, directionality in scintillator*

Unloaded scintillator phase: 780 t liquid scintillator
- characterisation of scintillator and backgrounds
- solar, supernova, reactor and geo neutrinos

Tellurium phase: 4 t of natural Te loaded to the LS
neutrinoless double beta decay!

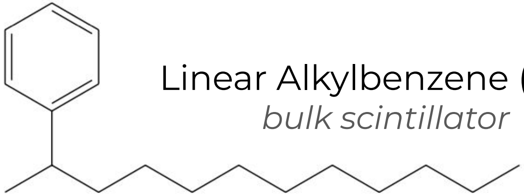


SNO+ Scintillator

Organic liquid scintillator mixture provides high light yield and can be purified to high degree to minimise radioactive backgrounds

- *multi-stage distillation, water extractions, N_2 and steam stripping, AV recirculation*

underground scintillator purification plant

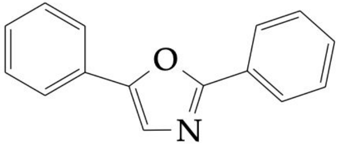


Linear Alkylbenzene (LAB)

bulk scintillator

\+ 2.2 g/L 2,5-Diphenyloxazole (PPO)

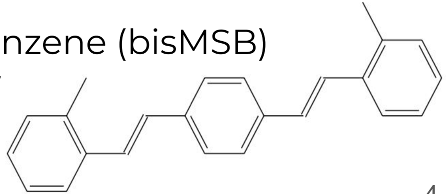
primary fluor



PPO top-up campaign finished in April 2022!

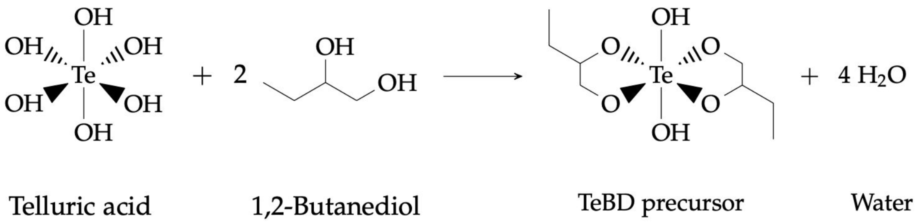
\+ 1,4-Bis(2-methylstyryl)benzene (bisMSB)

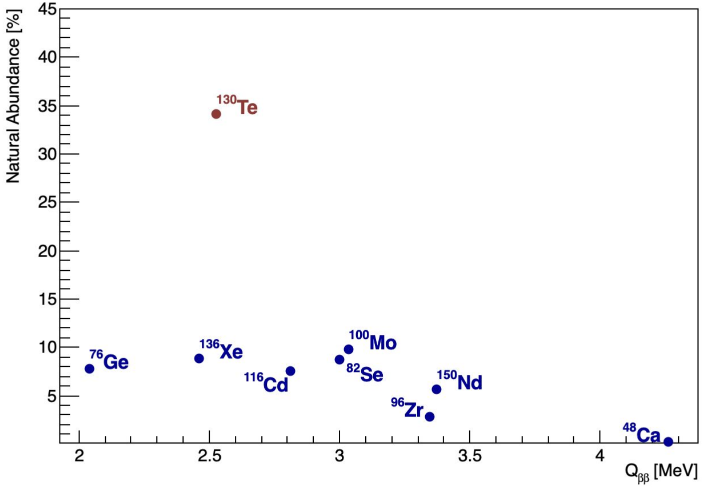
secondary fluor

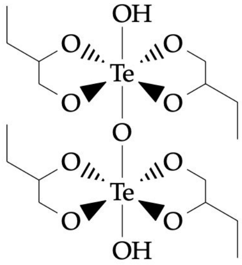


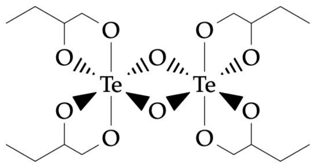
^{130}Te in SNO+

0.5% Te by weight loaded in LS in the first stage
Estimated light yield of 470 PMT hits/MeV with SNO+ loading technique









Tellurium Butanediol (TeBD) complex soluble in LS

^{130}Te as ββ isotope

High Q value (2.5 MeV)
High natural abundance (34 %)
Long 2νββ half-life (7.9x10^{20} yrs)

^{130}Te in SNO+

Two Te systems (purification & synthesis/loading) built underground
Telluric acid procured and stored underground since 2015 to reduce cosmogenic activation

TeA underground storage

Target 10^{-15} g/g for both ^{238}U and ^{232}Th chains for 0.5% Te phase

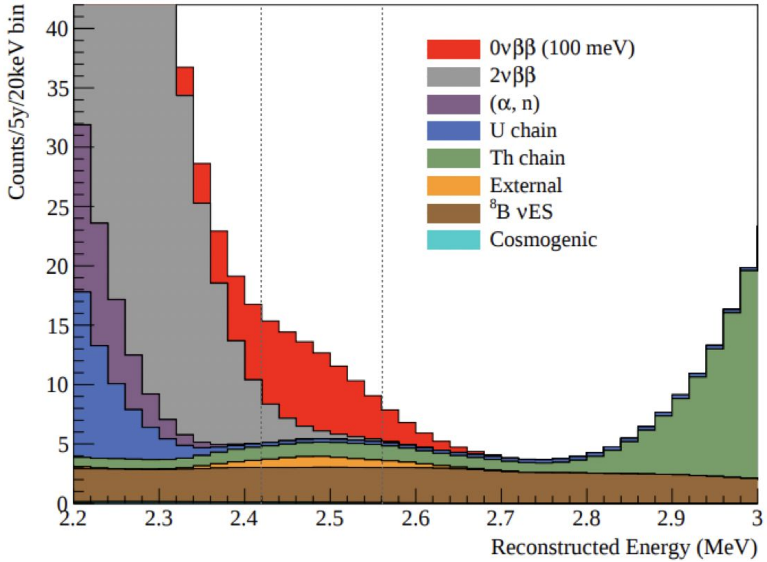
underground TeA purification plant

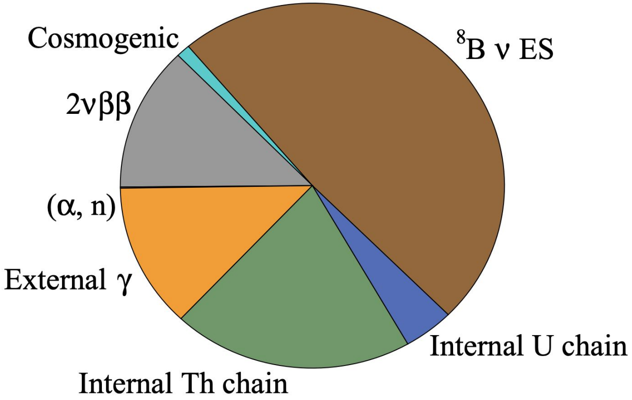
underground TeBD synthesis plant

10^4-10^5 purification factor

0νββ Search in SNO+ in ^{130}Te

9.47 background counts/yr → $T_{1/2}$>2.1 x 10^{26} yrs
after 5 yrs with 0.5 % Te (Phase I) from counting analysis

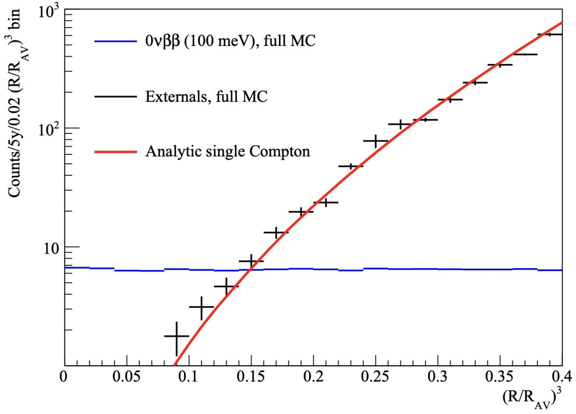




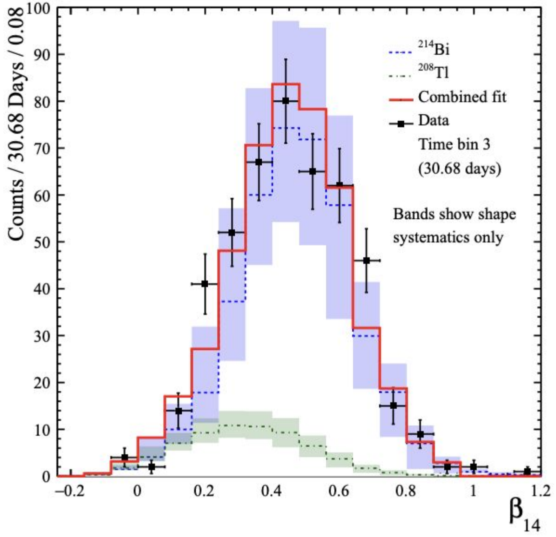
Using fiducial volume of 3.3 m
Region of interest -0.5 - 1.5σ: 2.42-2.56 MeV

External Backgrounds

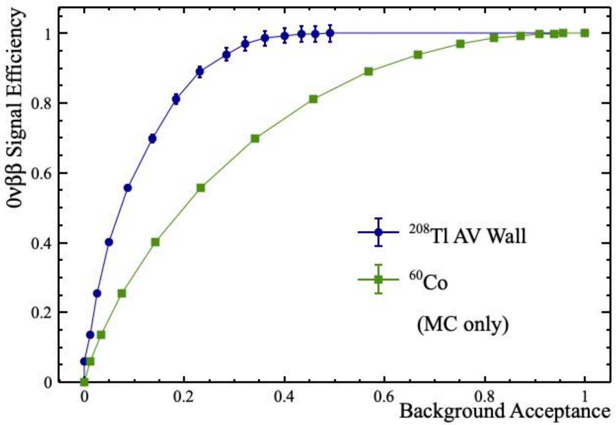
γs from decays (^{208}Tl & ^{214}Bi) in the AV, PMTs, ropes, external water



Fiducialisation is the primary strategy for rejecting externals



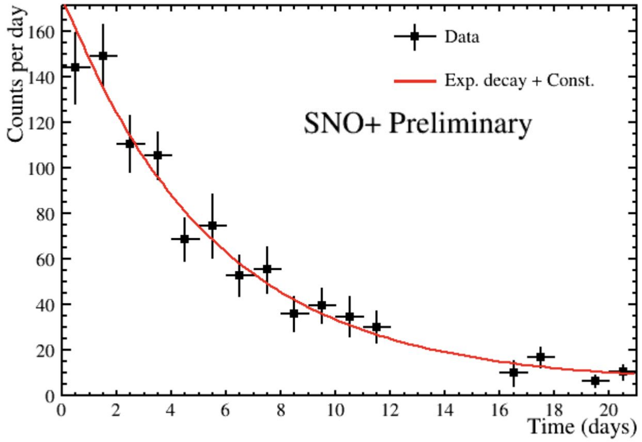
Fully measured in water phase and consistent with expectation Phys. Rev. D 99, 032008



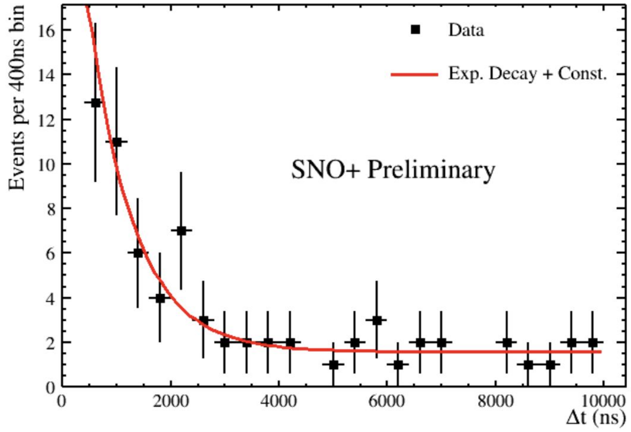
γ-β pulse shape discrimination (PDS) allows for additional rejection

Internal Backgrounds

Daughters of ^{238}U and ^{232}Th chains inside the AV
Mitigated by purification, cover gas system, coincidence tagging and α-β scintillator pulse shape discrimination



Daily rate of coincidence-tagged ^{214}BiPo decays to fit underlying U-chain contamination



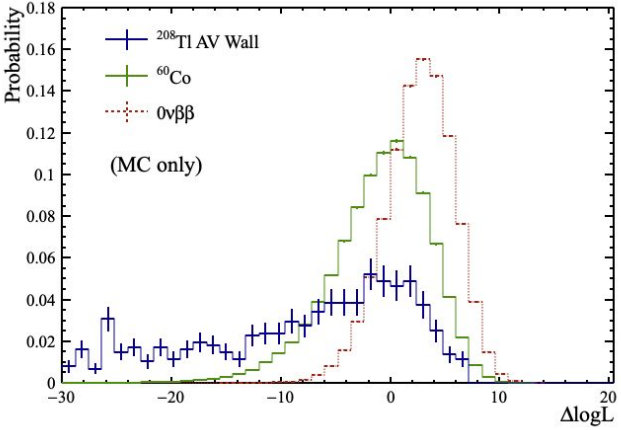
Fitted time difference of coincidence-tagged ^{212}BiPo events

cover gas system bags

Both ^{238}U and ^{232}Th chain contamination in unloaded scintillator measured to be 10^{-17} g/g

Cosmogenic Backgrounds

Decay of isotopes created by cosmic ray spallation on tellurium



Pulse shape discrimination (PSD) technique to classify multi-site (decays with γs) and single-site (pure β decays, 0νββ) energy depositions

Average path lengths in LS

~30 cm for 1 MeV γ

~0.5 cm/MeV for e-

However, all events reconstructed under the hypothesis of an e-
→ **multi-site events have wider time residual distributions**

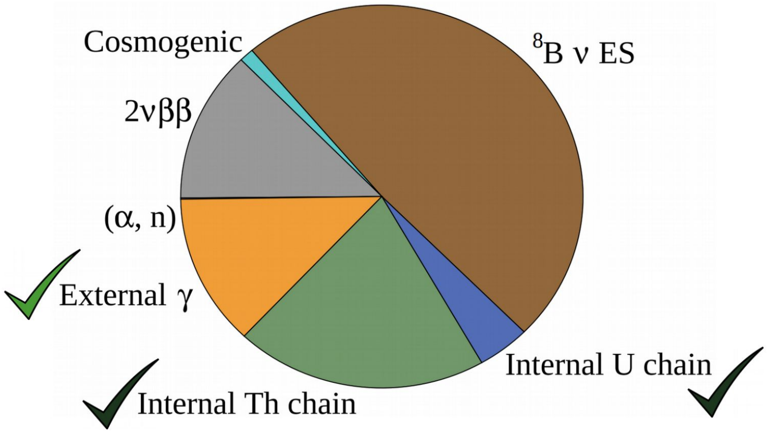
$$t_{res} = t_{hit} - t_{fit} - t_{tof}$$

Rejection by hard cuts but also used as a PSD dimension in a fit (see later)

Underground storage of Te allows for cosmogenics to decay before deployment, followed by purification

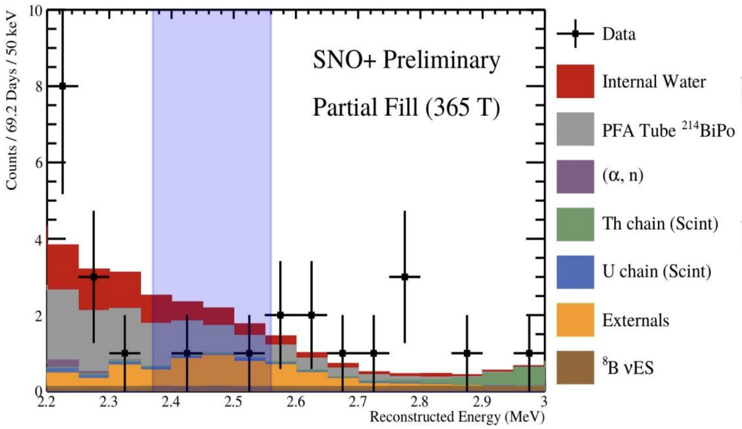
0νββ Search Background Summary

Pause in scintillator fill allowed for a target-out measurement of backgrounds



Measured and on target

Measured and on target for LAB



Fiducial volume of 4 m (vs 3.3 m) and >1 m above equator

Data from 1660 h during partial fill

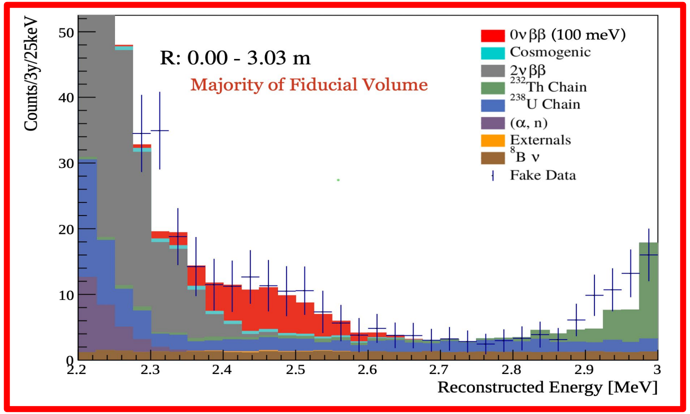
0νββ Signal Extraction

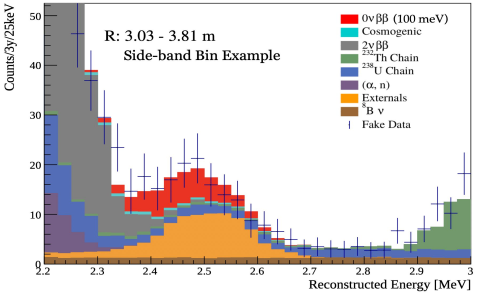
Backgrounds will be constrained with side bands in volume (up to 5.5 m) and energy (1.8-3.0 MeV)

PSD dimensions break degeneracy with any unexpected cosmogenic contamination

Multi-dimensional binned likelihood analysis using MCMC floating ~30 background normalisations

- analysis based on kernel density estimation in development



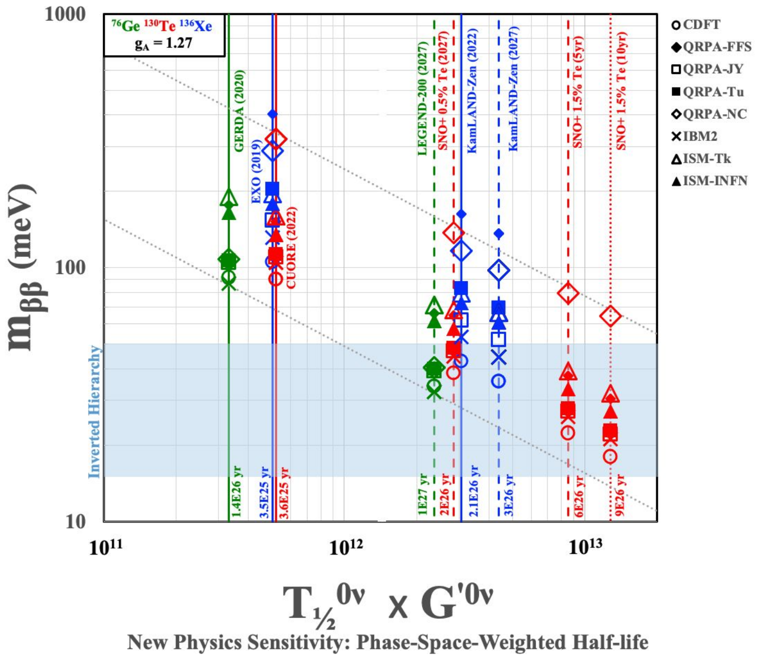


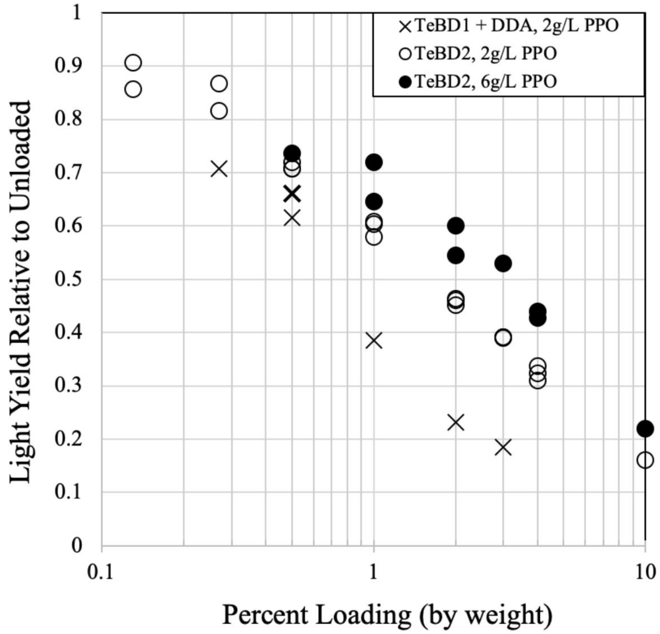
$T_{1/2}$>1.80 x 10^{26} yrs after **3 yrs** with 0.5 % Te (Phase I)

Discovery potential after 3 years of with 0.5% Te:
3σ sensitivity for $m_{\beta\beta}$= 80-194 meV

Future Prospects

SNO+ exposure easily scalable by loading more with improved loading techniques
Increasing loading to multiple % for Phase II





Conclusions

SNO+ is full of liquid scintillator and getting ready to load ββ isotope

All backgrounds on target for 0υββ search

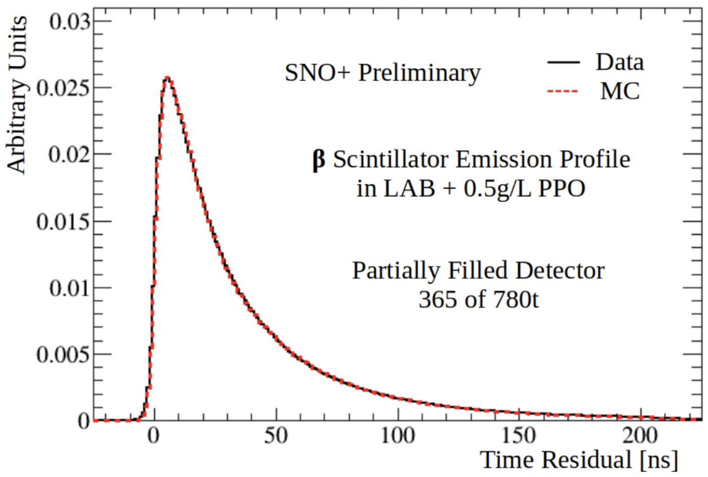
SNO+ aims to have world leading 0υββ sensitivity in ^{130}Te

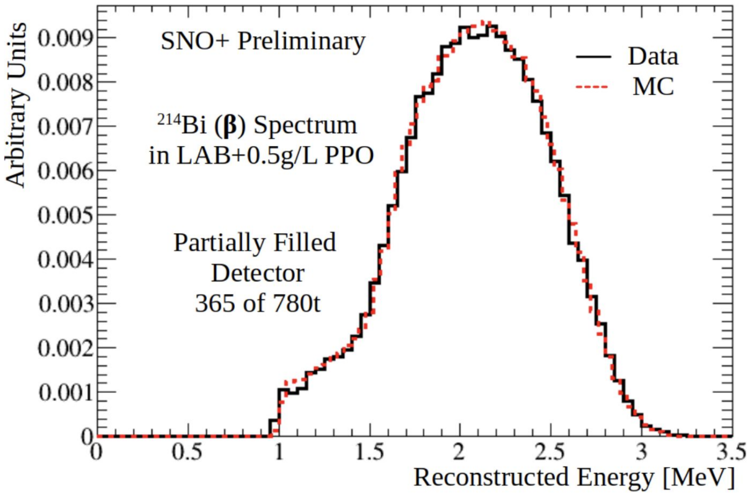
Thank you for your attention!

Back up: Internal Radioactivity Calibration

*^{214}Bi β and ^{214}Po α (not shown) decay in **tagged ^{214}BiPo coincidence** pairs as a calibration source*

Dataset from period of stable partially filled (365 t of scintillator) detector when filling was stopped due to the pandemic in 2020

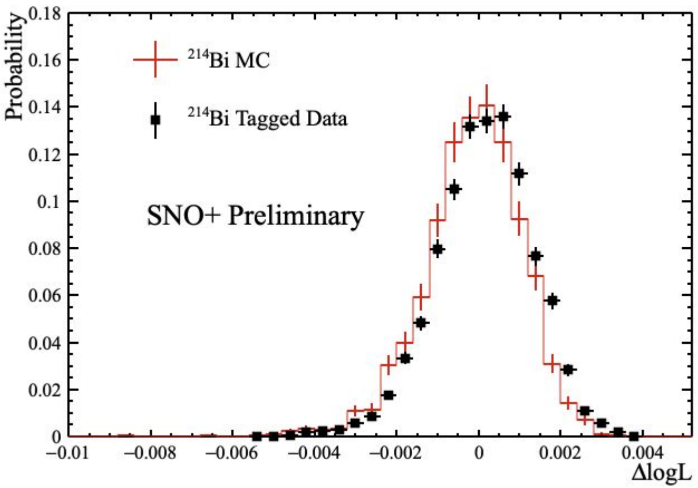


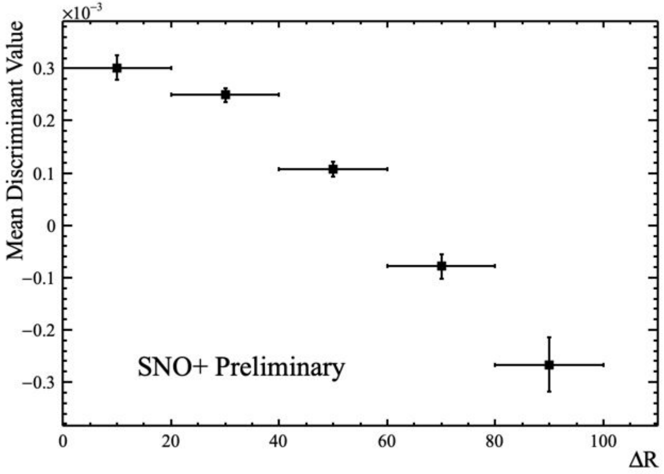


Back up: PDS Calibration

*^{214}Bi β and ^{214}Po α (not shown) decay in **tagged ^{214}BiPo coincidence** pairs as a calibration source*

Dataset from period of stable partially filled (365 t of scintillator) detector when filling was stopped due to the pandemic in 2020





Back up: Background Numbers

Partial fill ROI analysis:

Background	Expected Counts in Partial Fill ROI
Internal Water	1.8
PFA Tube ^{214}BiPo	2.9
Externals	2.5
$(\alpha$, n)	0
Th Chain (Scint)	0.1
U Chain (Scint)	0.3
^{8}B νES	0.5
Total Backgrounds	8.0

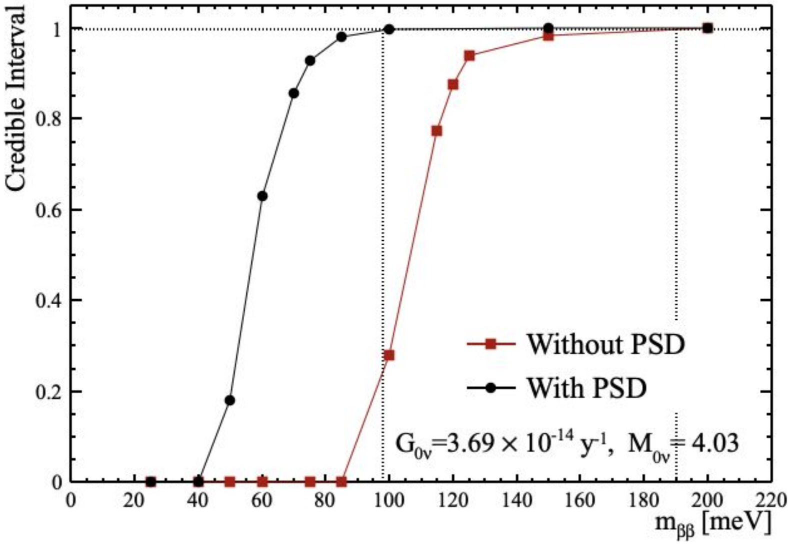
Scintillator natural radioactivity:
$4.7 \pm 1.2 \times 10^{-17}$ gU/gLAB
$5.3 \pm 1.5 \times 10^{-17}$ gTh/gLAB

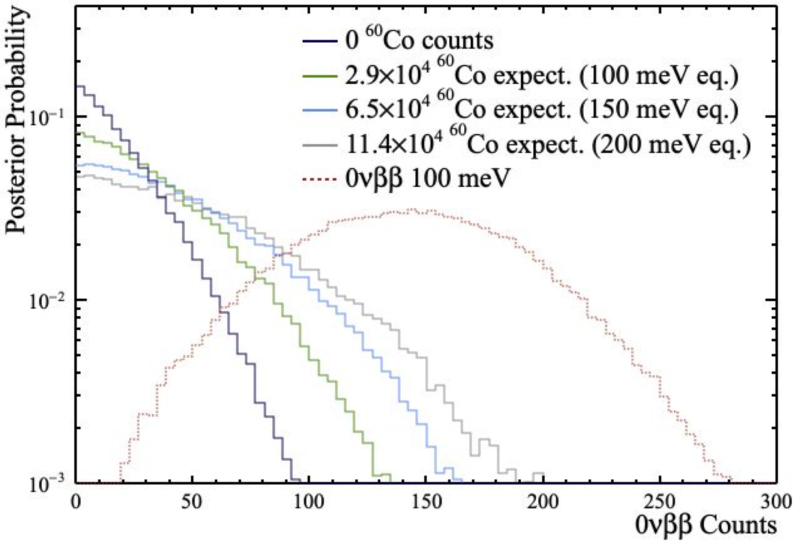
Externals:

Background	Rate (Fraction of Nominal)
AV+Ropes	$0.52 \pm 0.02^{+0.39}_{-0.28}$
External Water	$0.03 \pm 0.01^{+0.61}_{-0.03}$
PMT	$2.04 \pm 0.04^{+3.69}_{-1.20}$

Back up: 0νββ Signal Extraction with PSD

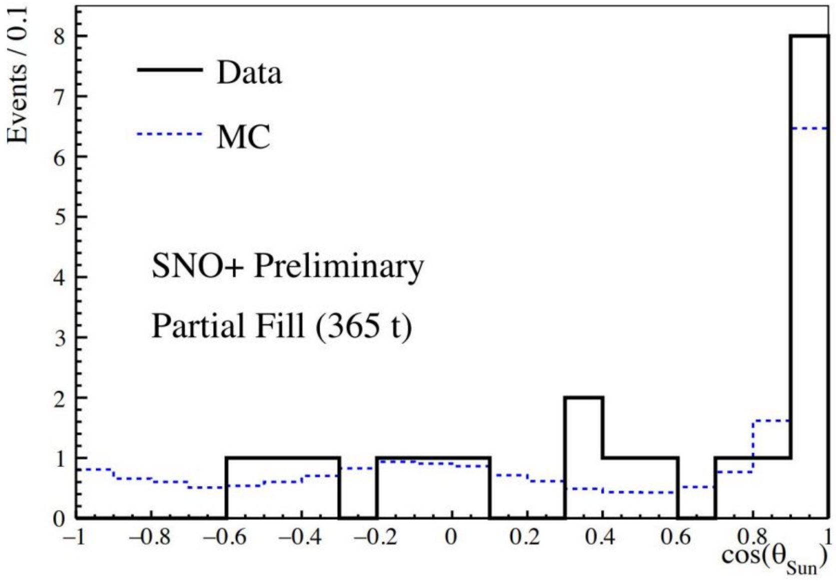
PSD breaks degeneracy between cosmogenic backgrounds and 0νββ
→ main gain for discovery rather than limit setting





DNP 2021

Back up: Directionality in Partial Fill



IoP APP/HEPP 2022 talk by J. Paton