The SNO+ Experiment

Hybrid Detector Workshop 2025, 5th June 2025

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for the SNO+ Collaboration

The SNO+ Experiment

Multi-purpose neutrino detector
at SNOLAB, Sudbury, Canada

2070 m rock overburden

~9300 photomultiplier tubes (PMTs)

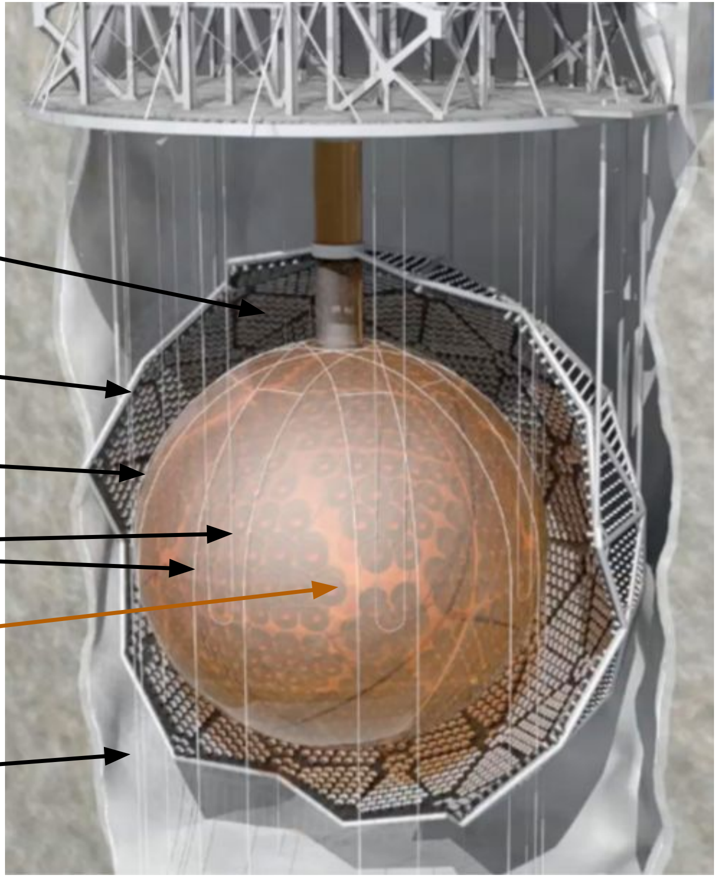
PMT support structure, 18m diameter

Acrylic vessel, 12 m diameter

Hold up and hold down ropes

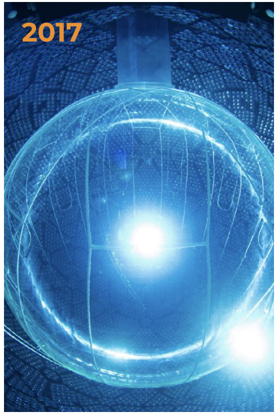
Target

7 kt ultra-pure water shielding



JINST 16, P08059

SNO+ Timeline

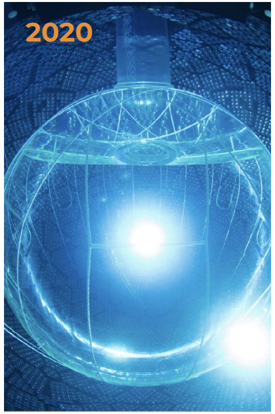


Water phase

905t ultra-pure water

detector calibration and external background measurements

[Phys. Rev. D 110, 122003](#)
[Phys. Rev. D 99, 032008](#)
[Phys. Rev. Lett. 130, 091801](#)

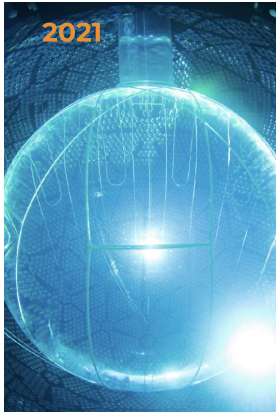


Partial-fill phase

paused filling due to COVID-19 at 370 t LS with 0.6 g/L PPO

measurement of scintillator backgrounds

[Eur. Phys. J. C 85, 17](#)
[Phys. Rev. D 109, 072002](#)

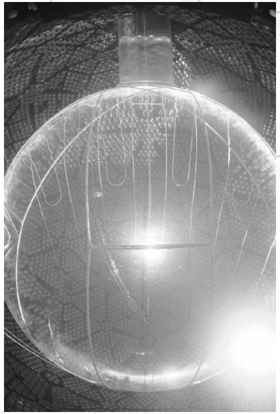


Scintillator phase

780 t LS
0.6 - 2.2 g/L PPO, 2.2 mg/L bisMSB

characterisation of scintillator and backgrounds

solar, supernova, reactor and geo neutrinos…



Tellurium phase

4t of natural Te initially

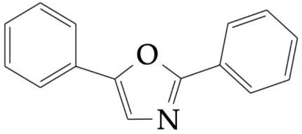
Neutrinoless double beta decay!

SNO+ Scintillator

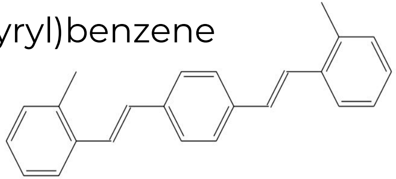
High yield bulk scintillator purified underground

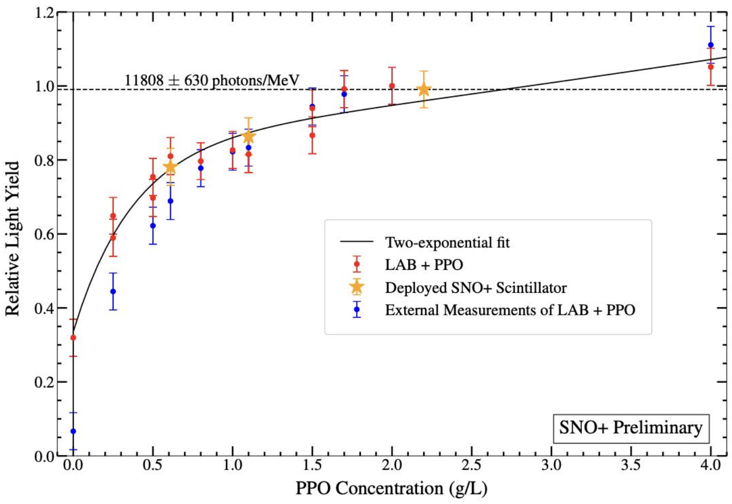
Linear Alkylbenzene (LAB)
bulk scintillator

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



\+ 2.2 mg/L 1,4-Bis(2-methylstyryl)benzene (bisMSB)
secondary fluor





PPO top-up campaign finished in April 2022

- PPO reduces LAB self-absorption and shifts photons to higher PMTs efficiency window

bisMSB added in July 2023

- Further shifting to PMT efficiency maximum
- Light yield increase of 1.5 observed

SNO+ Scintillator

High yield bulk scintillator purified underground

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bulk scintillator

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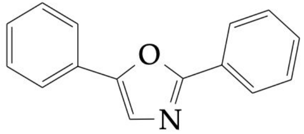

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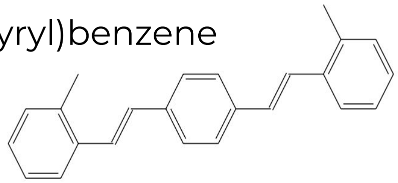
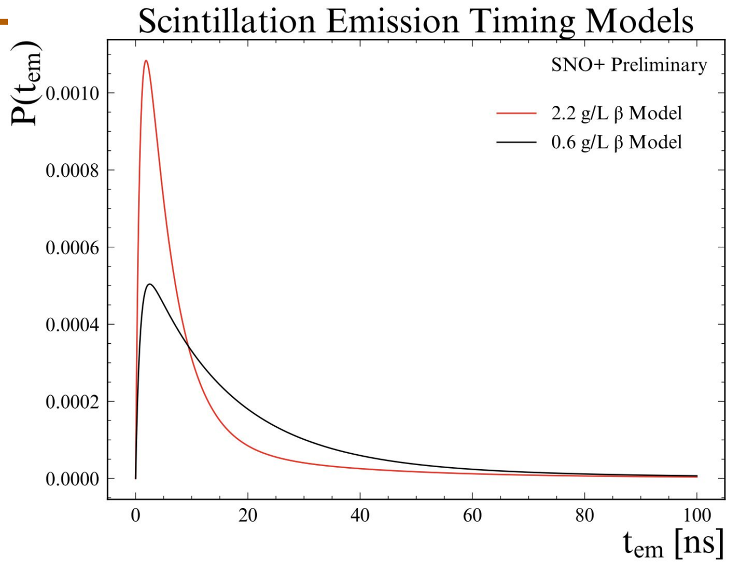
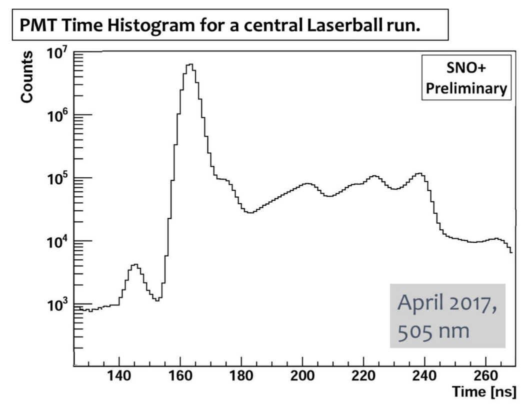




Scintillator mixture emission profile gets faster with more PPO

SNO+ PMTs

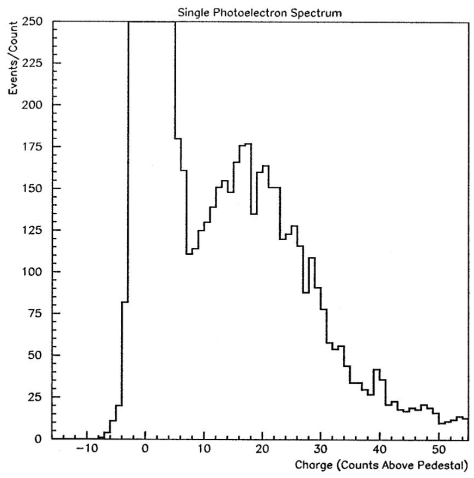
8" Hamamatsu R1408 PMTs from SNO



Transit Time Spread = 3.7 ns (FWHM)

Fast enough for scintillator emission time to dominate

Čerenkov light instantaneous



NIM A 449 (2000) 172-207

Each PMT equipped with a Winston cone concentrator

Total effective SNO coverage 54% at the start

Degraded over time to under 50%

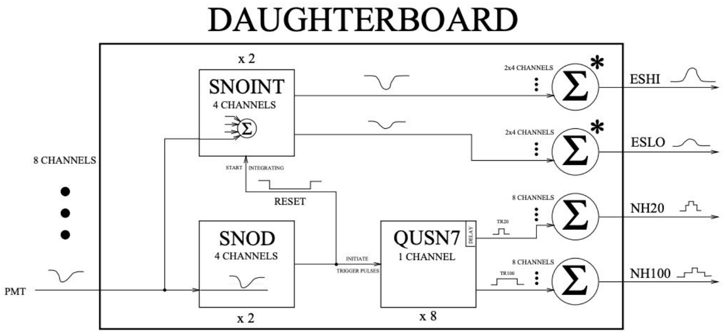
SNO+ Electronics

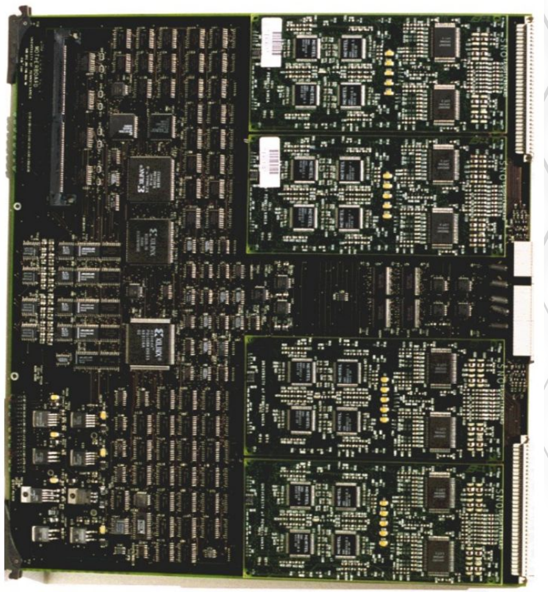
Readout electronics and DAQ partially upgraded since SNO to handle higher trigger rates and data volume in scintillator

Front End Cards (with 4 daughterboards each) record 4 quantities about a PMT over threshold in a ~400ns window:

3 charge integrations: high gain short window (QHS), high gain long window (QHL), low gain variable window (QLX)

and time via Time to Amplitude Conversion (TAC)

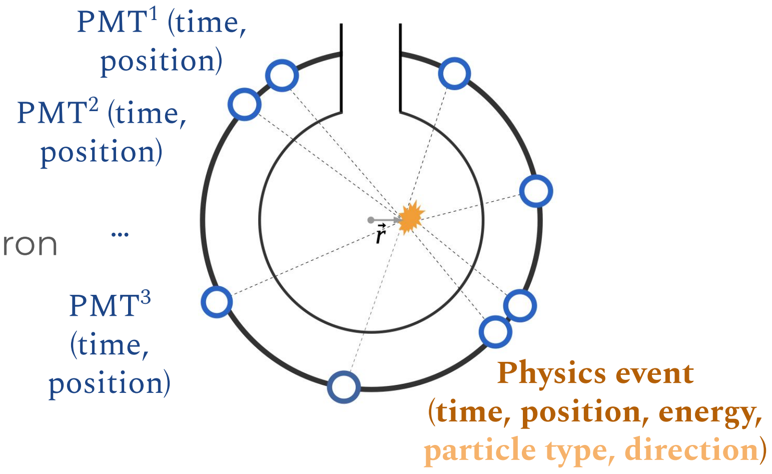




Very limited information about multiple photoelectrons hitting the same PMT

Event Reconstruction

All events first reconstructed under the hypothesis of an electron
Reconstruction utilises spherical symmetry of SNO+

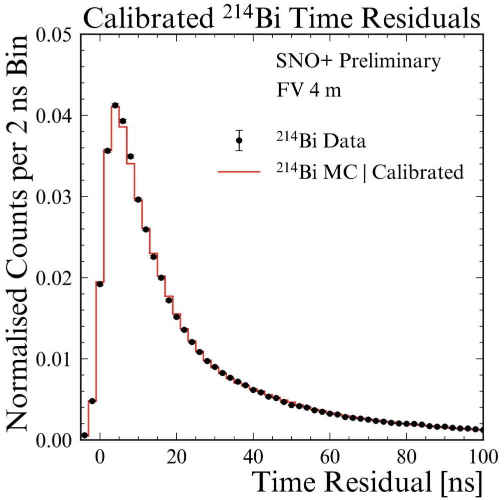


Vertex position & time reconstruction

Likelihood fit to the scintillator timing PDF, accounting for the photon time of flight

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

≤ ~20 cm 3D resolution (at 1 MeV and above)



Considerations

Not that important on its own, but fiducial cuts and input to energy, PID, direction…

Resolution gets improves rapidly with faster scintillator (and higher LY)

Event Reconstruction

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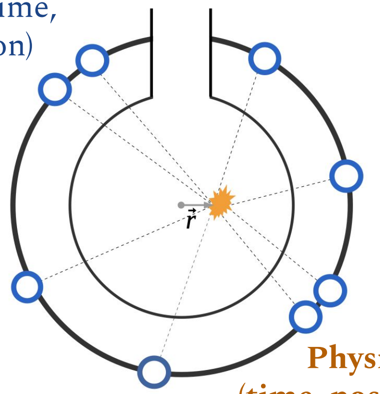
Reconstruction utilises spherical symmetry of SNO+



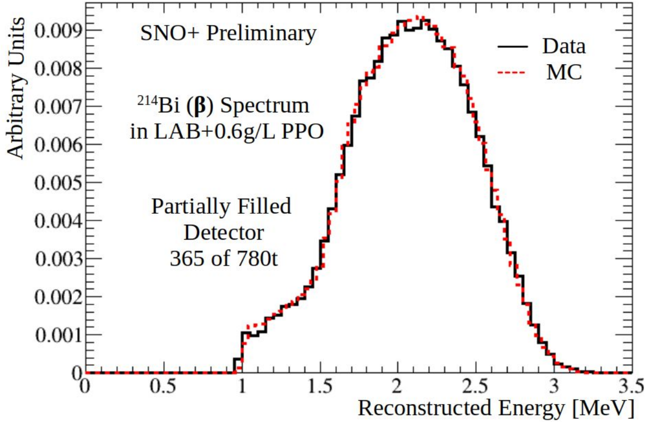
Vertex energy reconstruction

Linear energy estimator obtained from number of PMT hits and mutual positions with position-dependent correction

Resolution of ~5-6%√ E

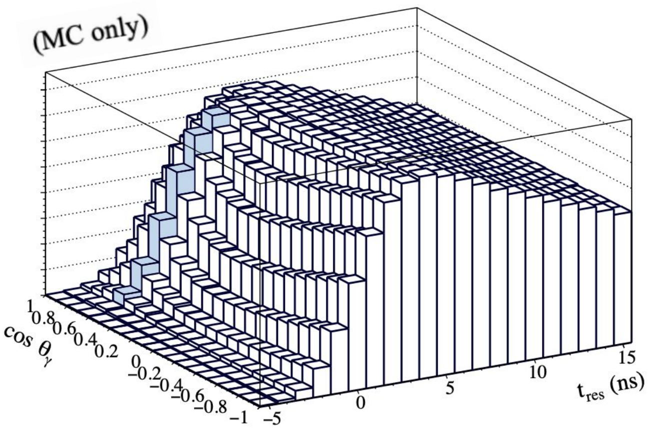
Considerations

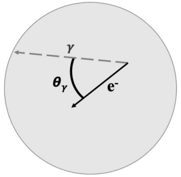
Resolution near Poisson limit from number of PMT hits



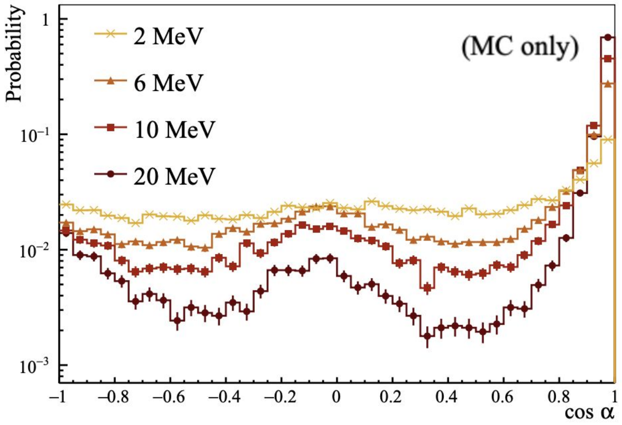
Direction Reconstruction

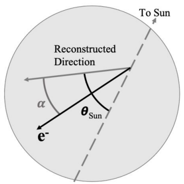
Relies on separation of small amount of Čerenkov light from scintillation light
Lower concentration of PPO in partial fill led to slower scintillation emission profile





θ_γ = angle between event direction and hit PMT with respect to event position





α = angle between reconstructed and true event direction

Likelihood fitter with a 2D PDF in θ_γ and time residuals using the fitted position

Direction expected to be peaked in the Sun's direction for ^{8}B solar neutrinos

Phys. Rev. D 109, 072002

Direction Reconstruction

Relies on separation of small amount of Čerenkov light from scintillation light
Lower concentration of PPO in partial fill led to slower scintillation emission profile

Events above ~5 MeV expected to all be solar neutrinos

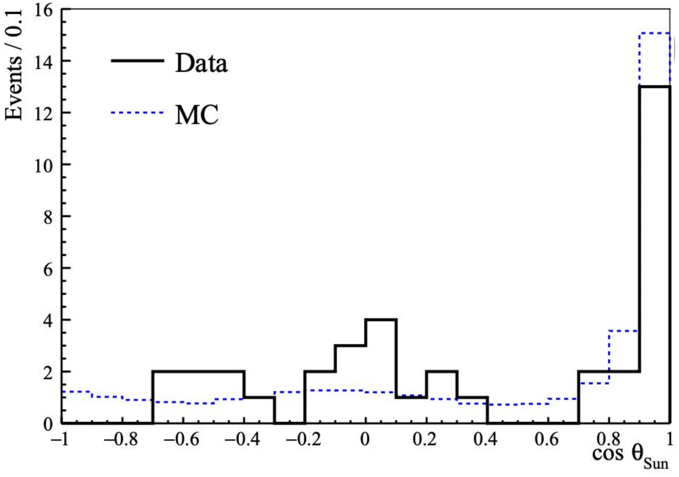
20 ^{8}B events in partially filled detector
(0.6 g/L PPO, 92 days livetime)

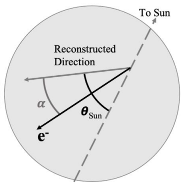
Event-by-event direction reconstruction in liquid scintillator!

High refractive index of LAB (1.5) results in more Čerenkov light and **low density** results in fewer scattering compared to water

→ **longer and straighter tracks**

compensating for some of the overwhelm of scintillation photons

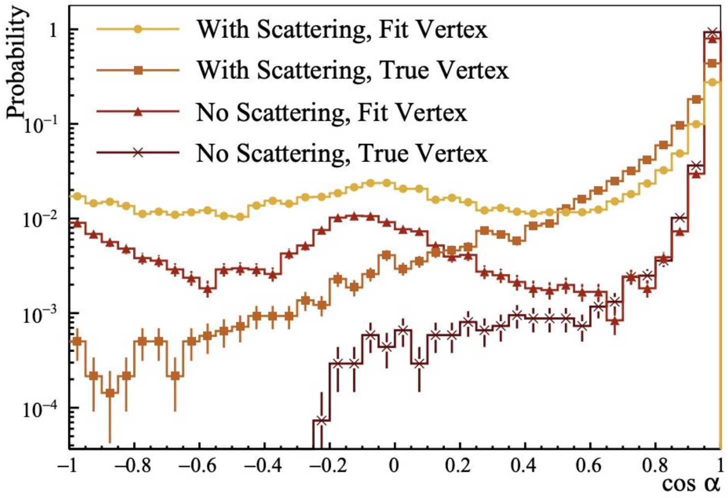




θ_{Sun} = angle between reconstructed event direction and direction from the Sun

Directionality Challenges

- With optimal PPO concentration, scintillation light faster and more abundant leading to harder discrimination
- Multiple **electron scattering**
  - reduces at higher energies
- **Position reconstruction bias** along the particle direction ("drive")
  - Čerenkov light pull, but also present without it to lesser extent
- Directionality highly sensitive to **optical calibration**

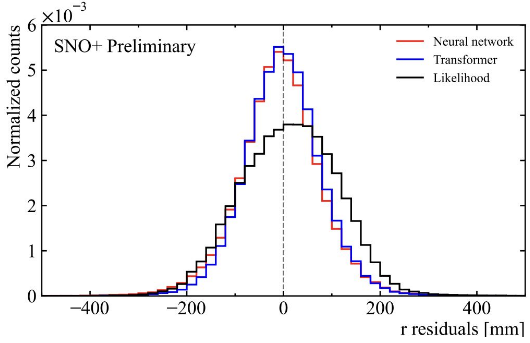


Directionality Challenges - Outlook

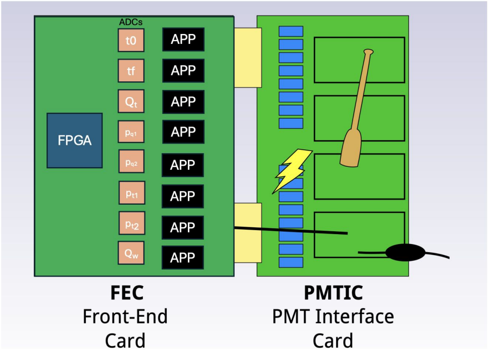
- Development of **position fitters** less susceptible to drive
  - Machine learning models are proving useful for comparisons and understanding

- **Electronics upgrade** for SNO+ proposed, possibly with Analog Photon Processor (APP) adding more features and enabling access to multi-PE regime
  - Overall sensitivity improvement due to improved reconstruction, i.e. beyond directionality

- Internal **calibration** through laserball deployment in scintillator to reduce systematics on optical model



FEC+ Pre-pre-Conceptual Design



Conclusions

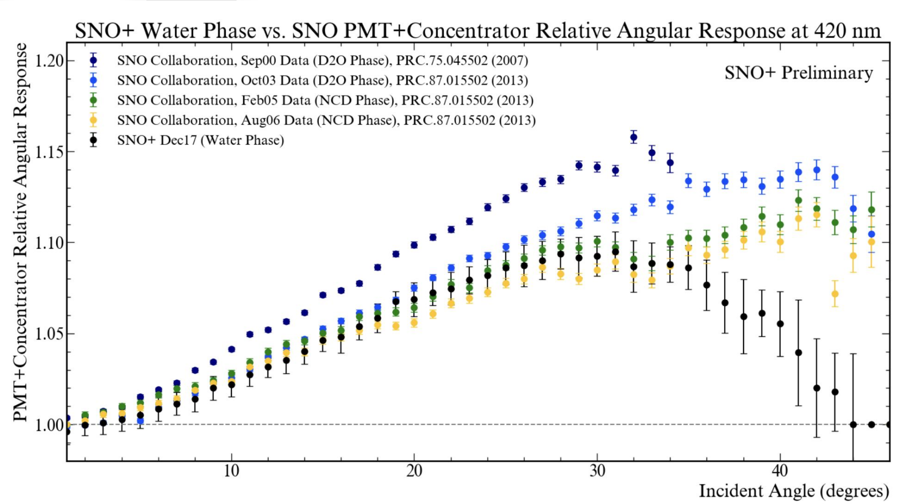
SNO+ is a large scale well-understood operating scintillator detector: while not hybrid by design, there are valuable lessons

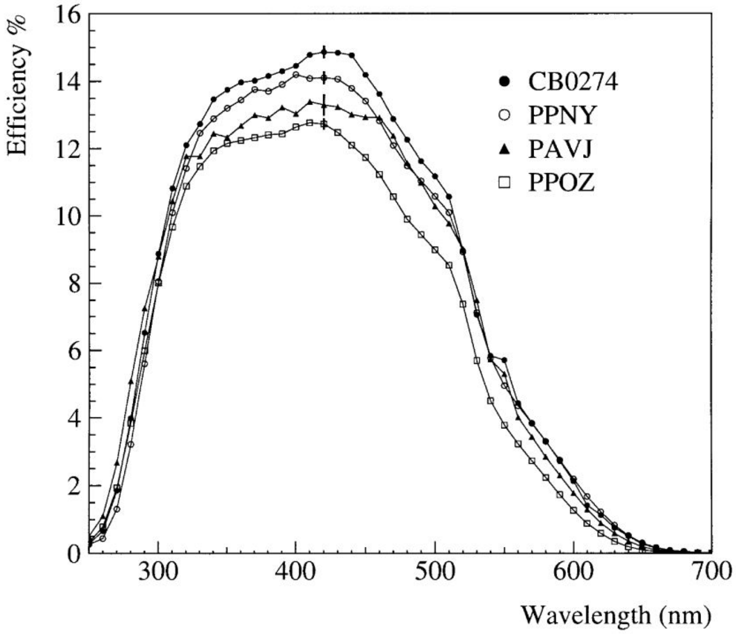
Event-by-event direction reconstruction < 10 MeV in a liquid scintillator detector demonstrated during partial fill (LAB+ 0.6 g/L PPO)

Work is ongoing on how we can continue to leverage such capabilities now with even higher light yield

Thank you for your attention!

Back up: SNO+ PMTs

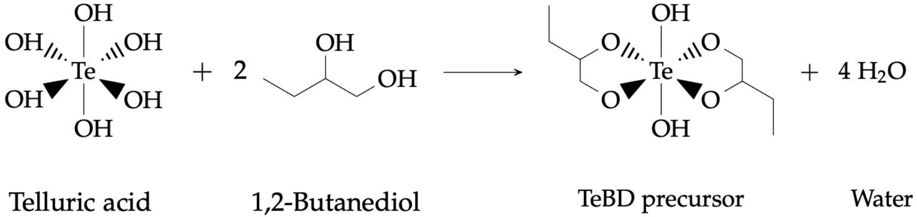


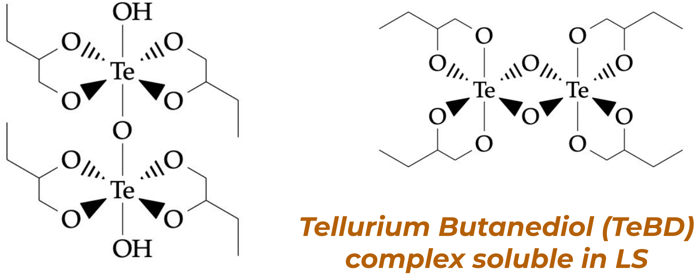


NIM A 432 (1999) 364-373

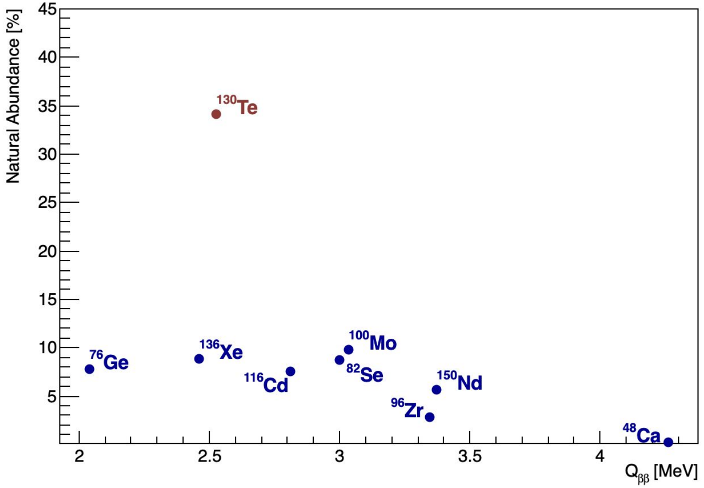
Back up: ^{130}Te in SNO+

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



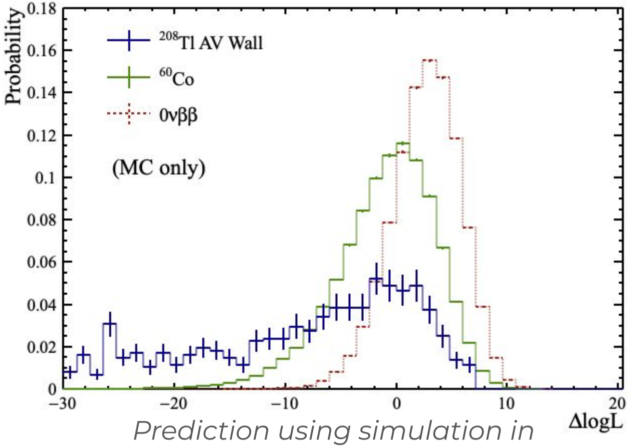
^{130}Te as ββ isotope

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

Back up: Multi-site Event Classification

Pulse shape discrimination (PSD) technique to classify multi-site (radioactive decays with γs) and single-site (pure β decays, 0νββ) energy depositions based on Dunger & Biller [NIM 943, 2019]

Multi-site classification values



Prediction using simulation in Te-loaded scintillator

Average path lengths in LS

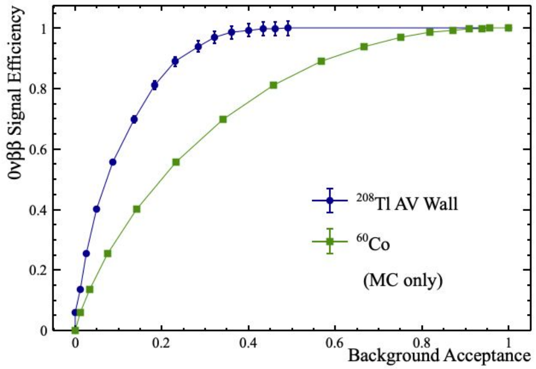
~30 cm for 1 MeV γ

~0.5 cm/MeV for e-

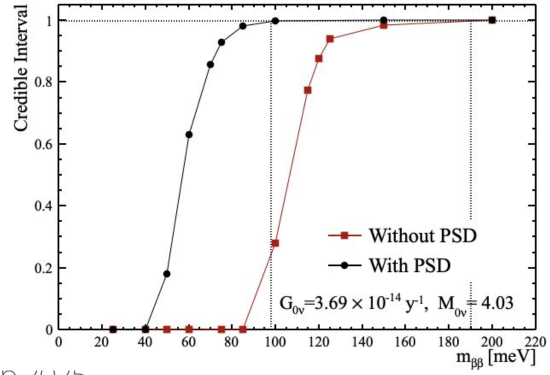
→ **multi-site events have wider time residual distributions**

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

Multi-site rejection using hard cuts



0νββ 3 year sensitivity with 0.5% Te



Rejection by hard cuts on classifier value but also through use as an additional dimension in likelihood fits

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Pulse shape discrimination (PSD) technique to classify multi-site (radioactive decays with γs) and single-site (pure β decays, 0νββ) energy depositions based on Dunger & Biller [NIM 943, 2019]

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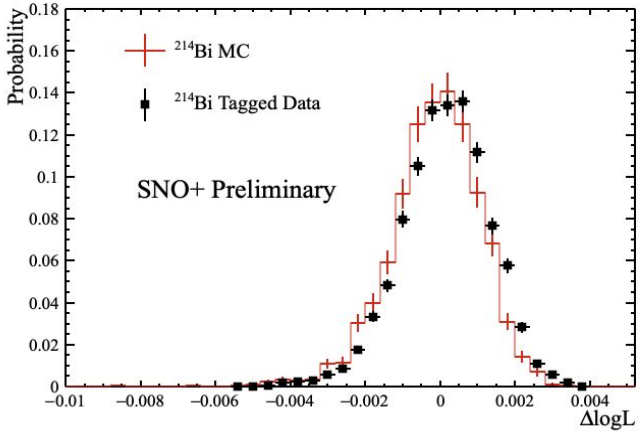


Dataset from period of stable ***partially filled detector*** *(365 t of scintillator) - agreement expected to improve with ongoing detector calibrations*

Average path lengths in LS

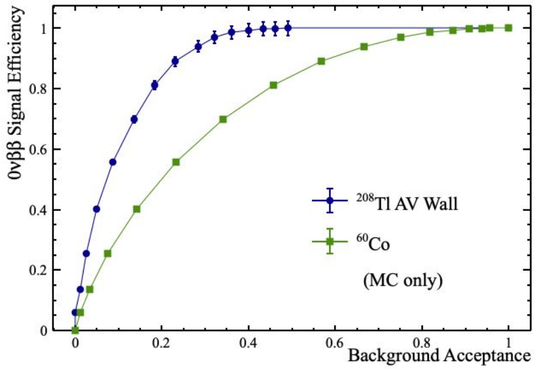
~30 cm for 1 MeV γ

~0.5 cm/MeV for e-

→ **multi-site events have wider time residual distributions**

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

Multi-site rejection using hard cuts



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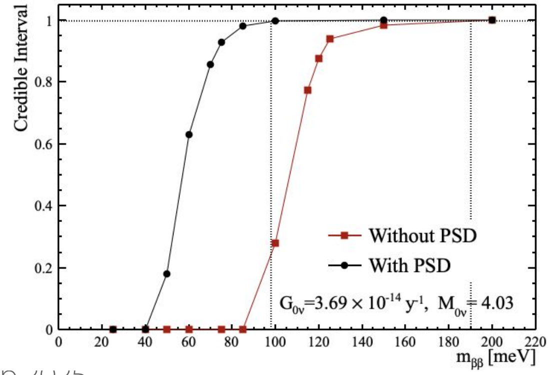
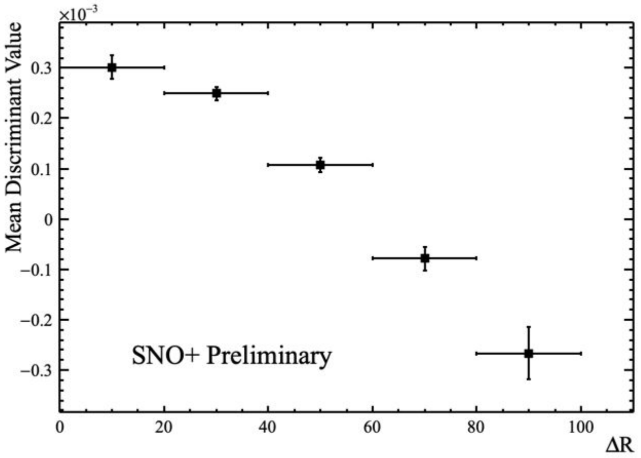
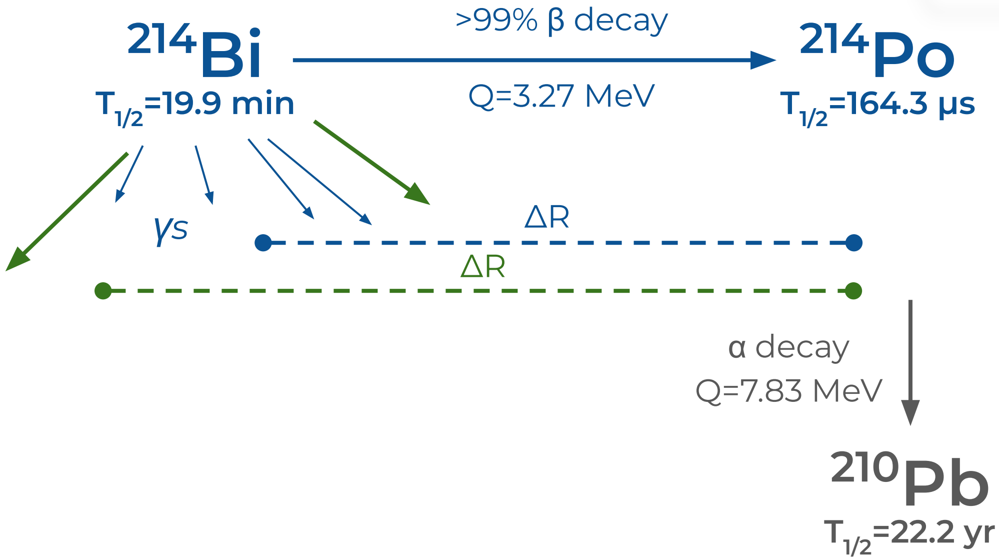


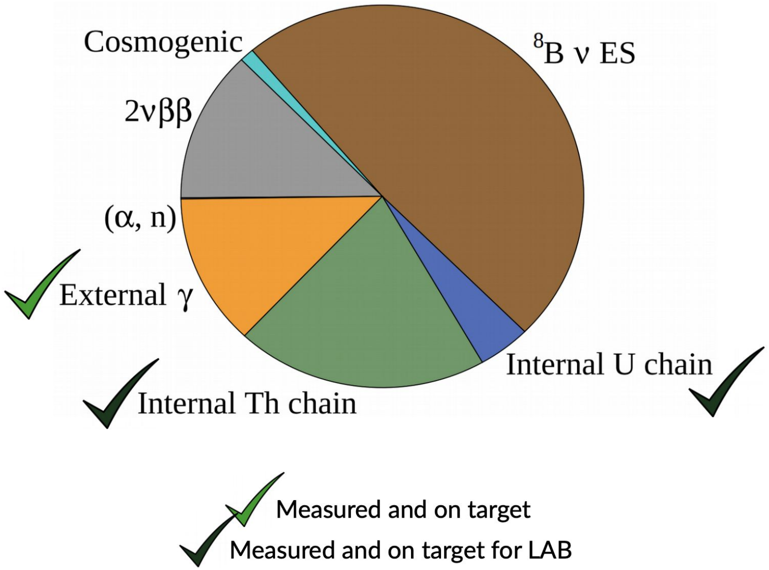
Back up: Multi-site Event Calibration

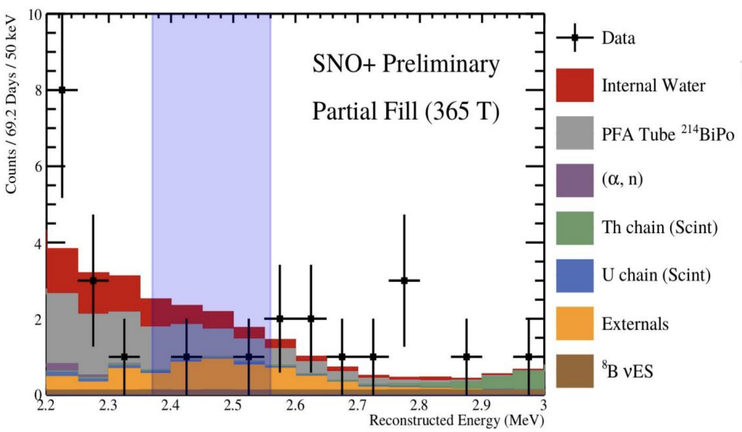
^{214}Bi β decay in tagged ^{214}BiPo coincidence pairs as a source of multi-site events for calibration





Back up: 0νββ Search Background Summary





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

Data from 1660 h during partial fill

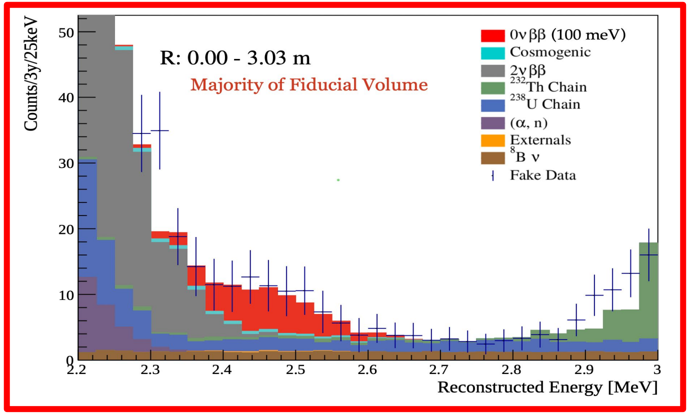
Back up: 0νββ Search Sensitivity

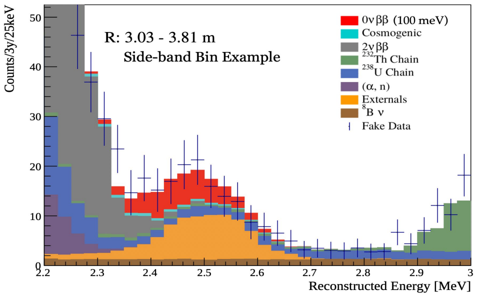
Backgrounds will be constrained with side bands in volume (up to 5.5 m) and energy (1.8-3.0 MeV)

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