Astrophysical Neutrinos

Morgan Askins, for the SNO+ Collaboration

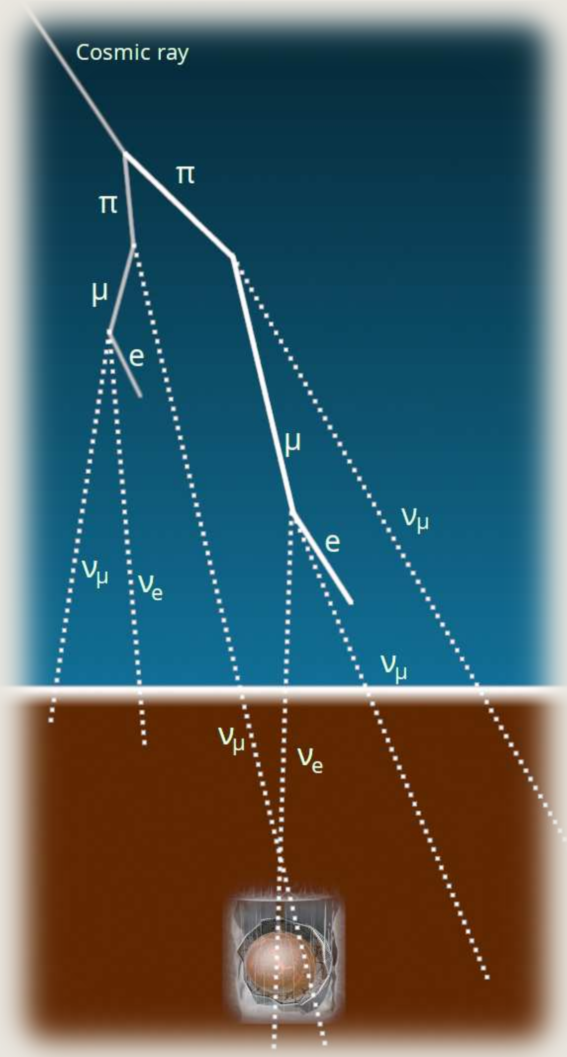
Snoplus Detector

Located deep underground in Sudbury, Ontario at SNOLab, the SNO+ detector is an upgrade to the SNO detector, designed to explore many neutrino-related physics topics, and ultimately search for neutrino-less double beta decay.

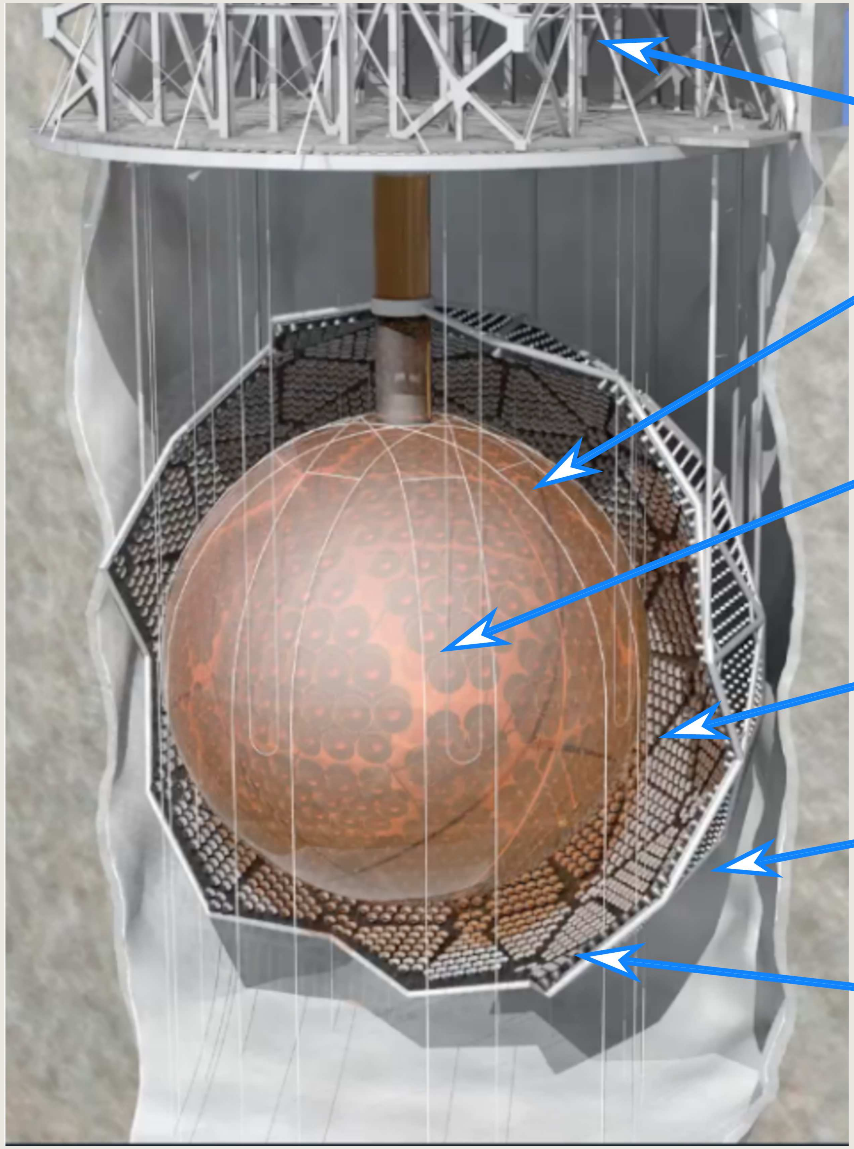
→ Modern underground lab provides high levels of cleanliness

→ 6800 ft. overburden significantly reduces muon flux—ideal for rare event searches.

Full detector details:
JINST 16 (2021) 08, P08059



Snoplus Detector



Overburden: 6800 ft. (5890 m.w.e.)

Acrylic Vessel (12 m Diameter)

905 Tonnes H_2O (phase I)
780 Tonnes Te-doped Scintillator (phase II)

1700 Tonnes H_2O Inner Buffer

5700 Tonnes H_2O Outer Buffer

$\sim$9300 PMTs

SNO+ Physics Goals

→ Water Phase

- Search for invisible nucleon decay
- Measure ^{8}B solar ν flux
- Characterize backgrounds from detector components
- Measure neutron capture cross-section in water

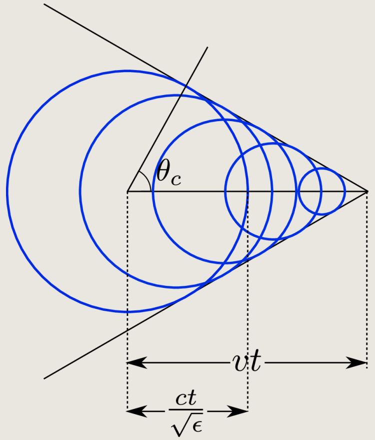
→ Pure Scintillator Phase

- Measure reactor and geo $\bar{\nu}_e$
- **Ready to handle supernova burst measurements**
- Characterize scintillator backgrounds
- **Precision solar ν measurements**
- Demonstration of directionality in liquid scintillator

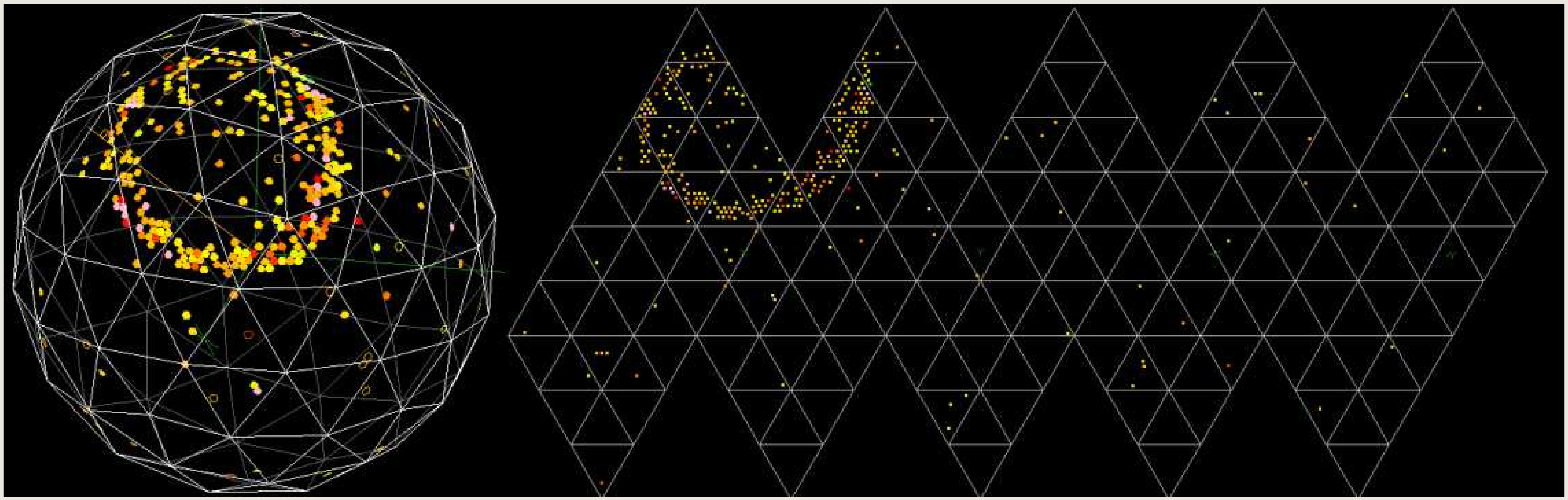
→ Te-loaded Scintillator Phase

- Search for neutrinoless double beta decay
- Continuation of pure scintillator physics

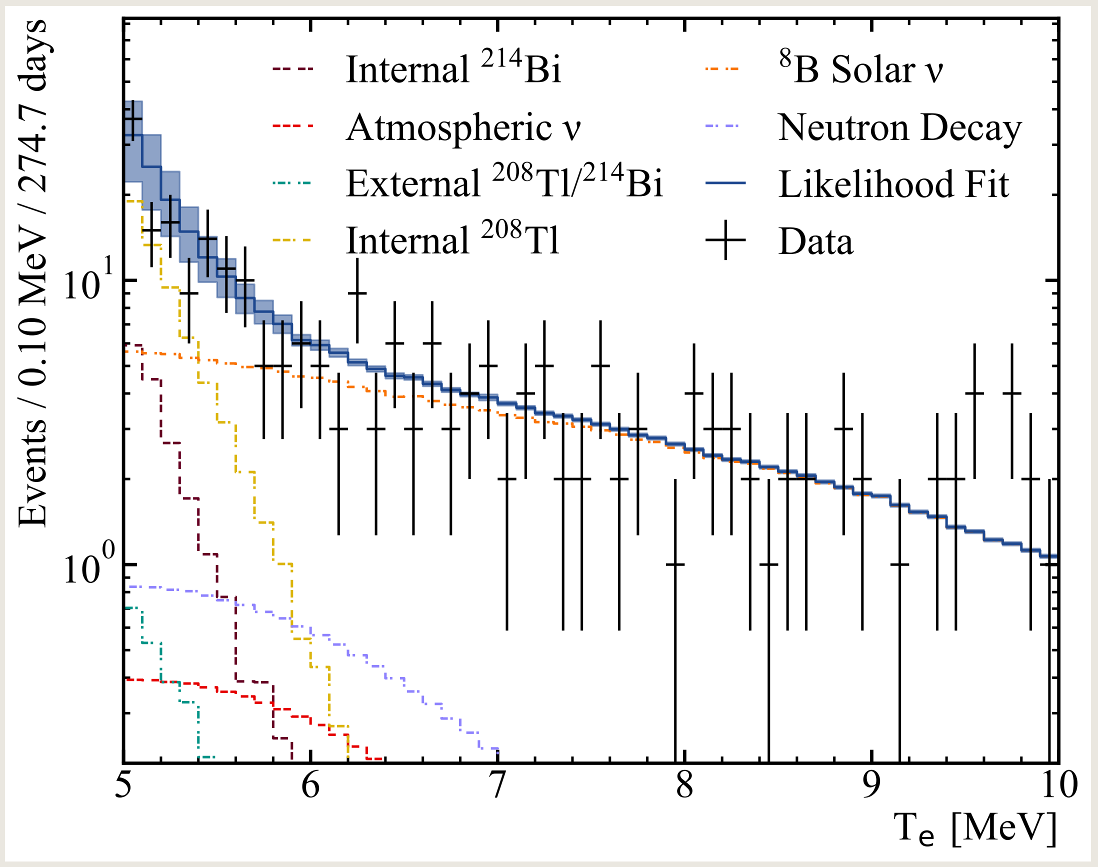
Water Phase



→ Water phase used for detector commissioning, as well as physics data taking.
→ Light emission only through Cherenkov radiation.
→ Cherenkov provides directional information useful for solar ν.
→ Energy resolution is statistically limited by low light output.

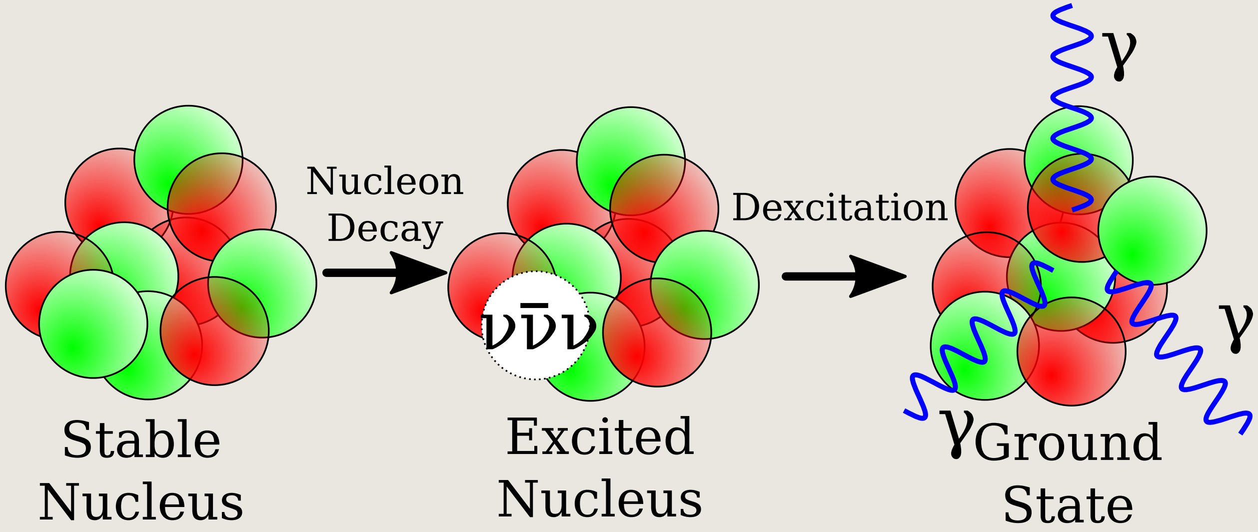


Invisible Nucleon Decay



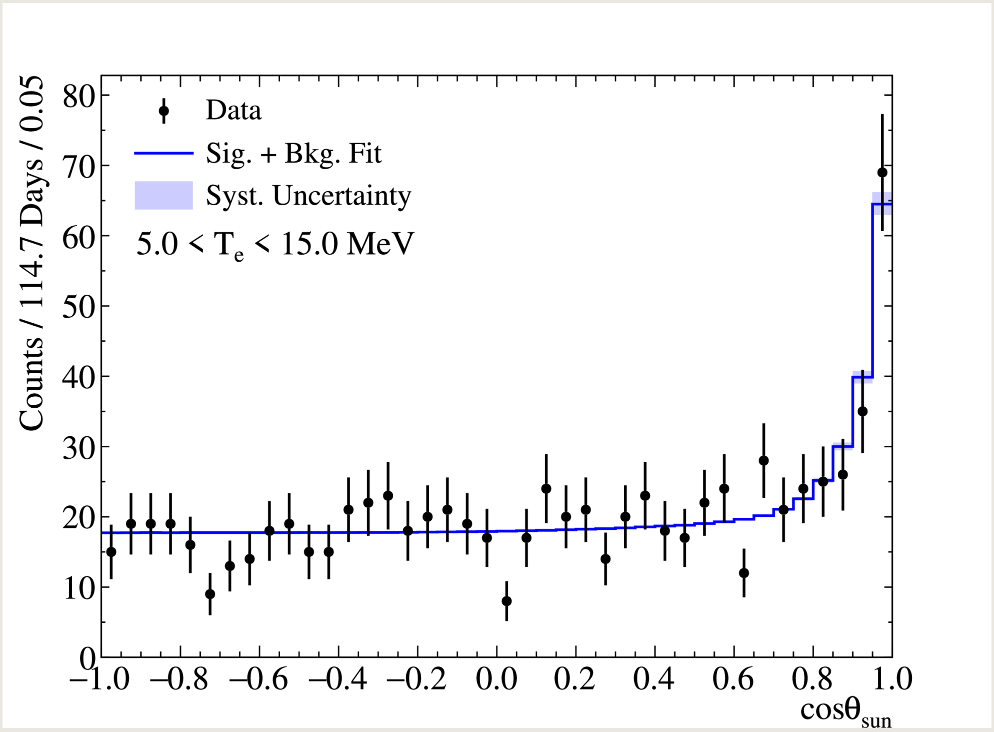
Phys. Rev. D 105 (2022) 11, 112012

Decay Mode	Partial Lifetime
n	9.0×10^{29}
p	9.6×10^{29}
pp	1.1×10^{29}
pn	6.0×10^{28}
nn	1.5×10^{28}



Solar Flux (updated results in progress)

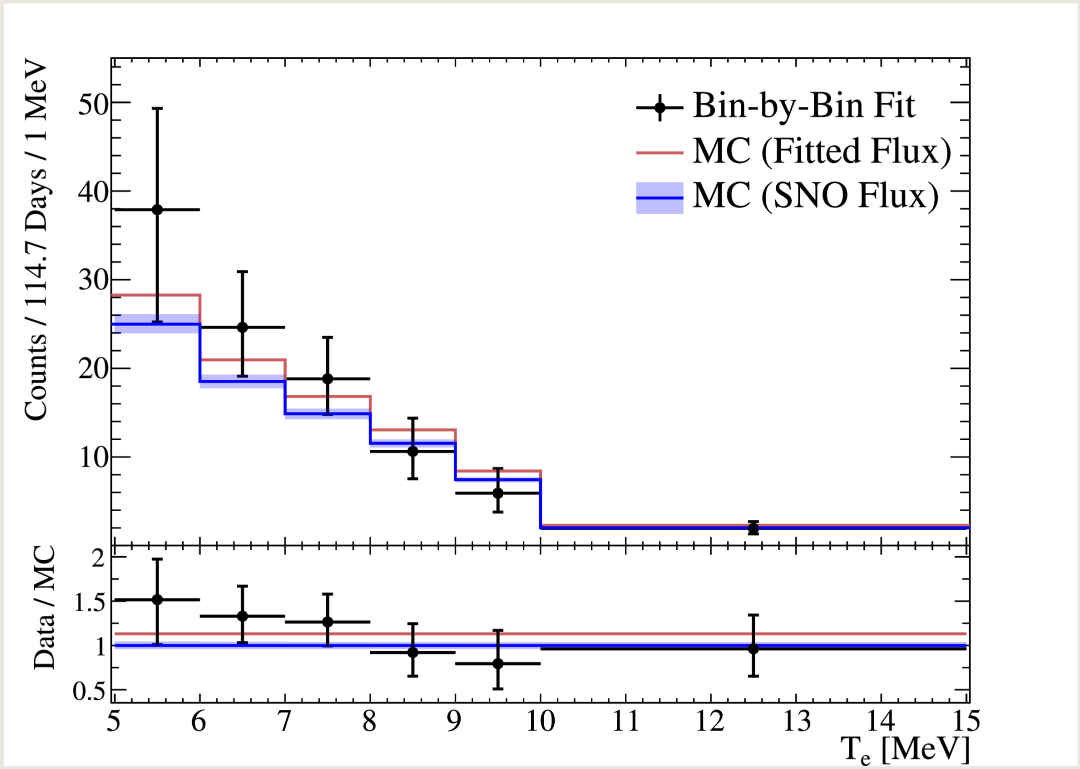
Event direction in water shows clear evidence for solar neutrinos on top of a flat background.



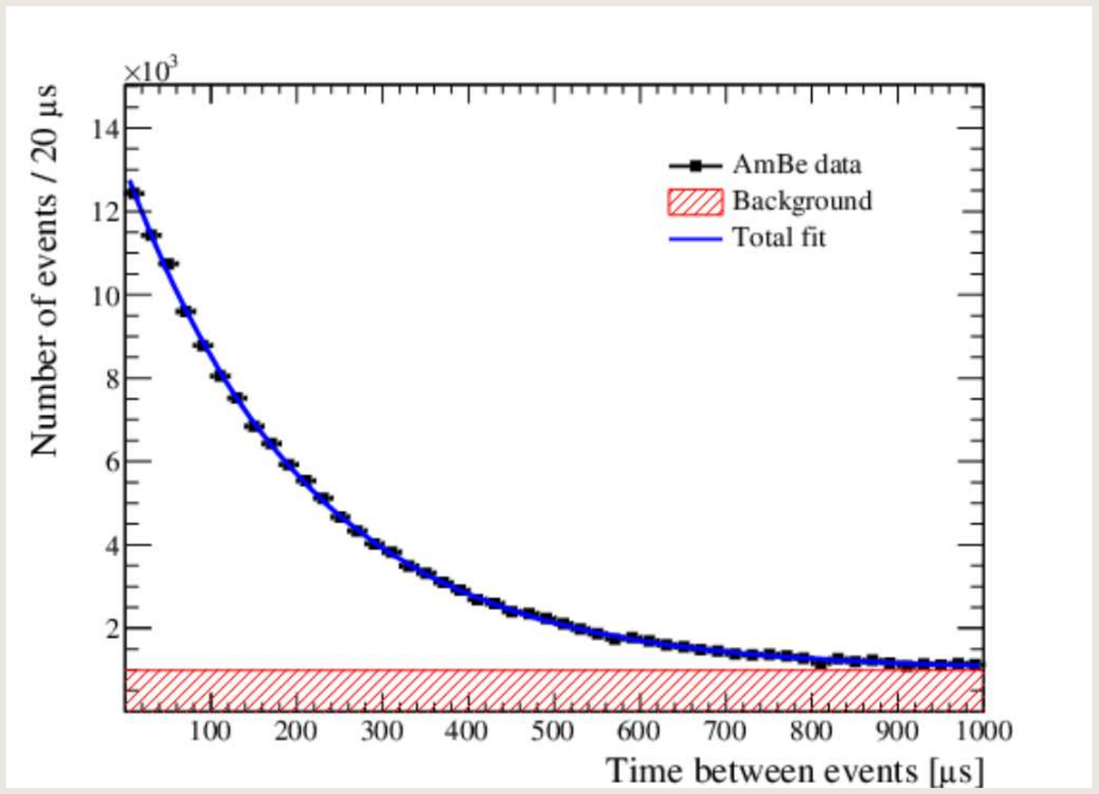
Phys. Rev. D. 99 (2019) 1, 012012

Measured flux consistent with SNO and Super-K

$$\Phi_{^8B} = 5.95^{0.75}_{-0.71}(\text{stat})^{0.13}_{-0.10}(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$



Neutron-proton Capture



Phys. Rev. C. 102 (2020) 1, 014002

Measurement of thermal neutron-proton capture cross-section with high detection efficiency in pure water.

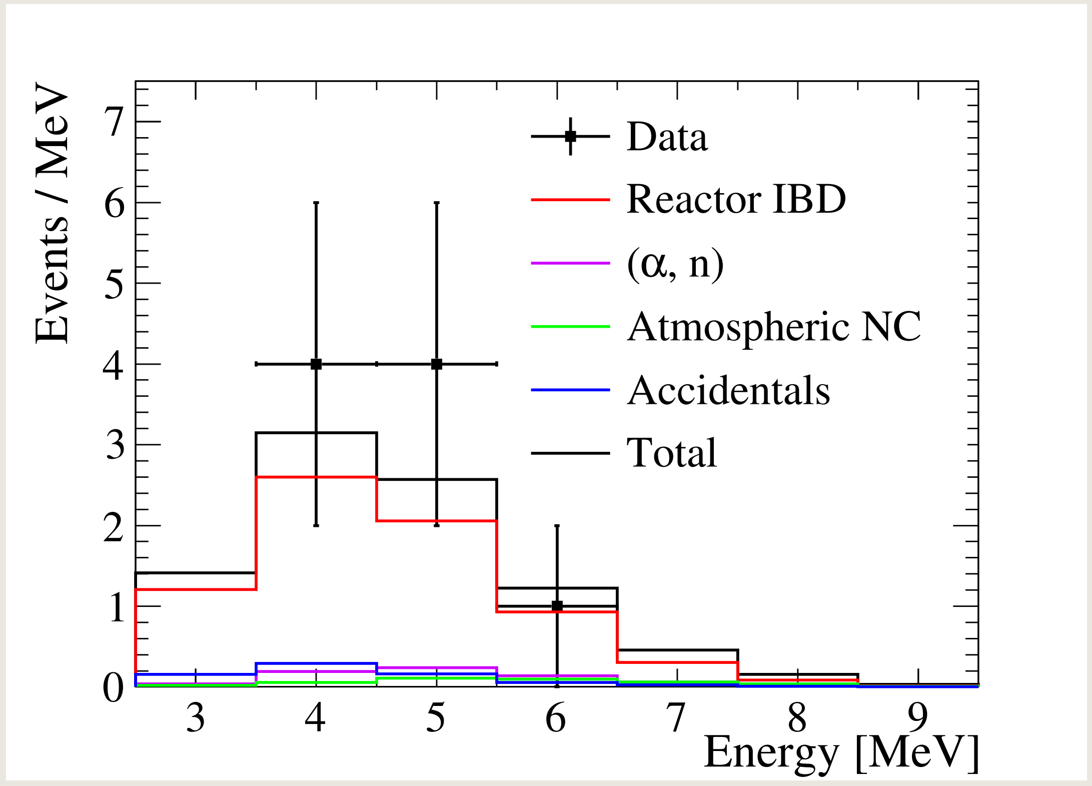
Efficiency [%]	$\tau[\mu s]$
49.09 ± 0.39	$202.35^{+0.87}_{-0.76}$

With a thermal cross-section consistent with dedicated experiments

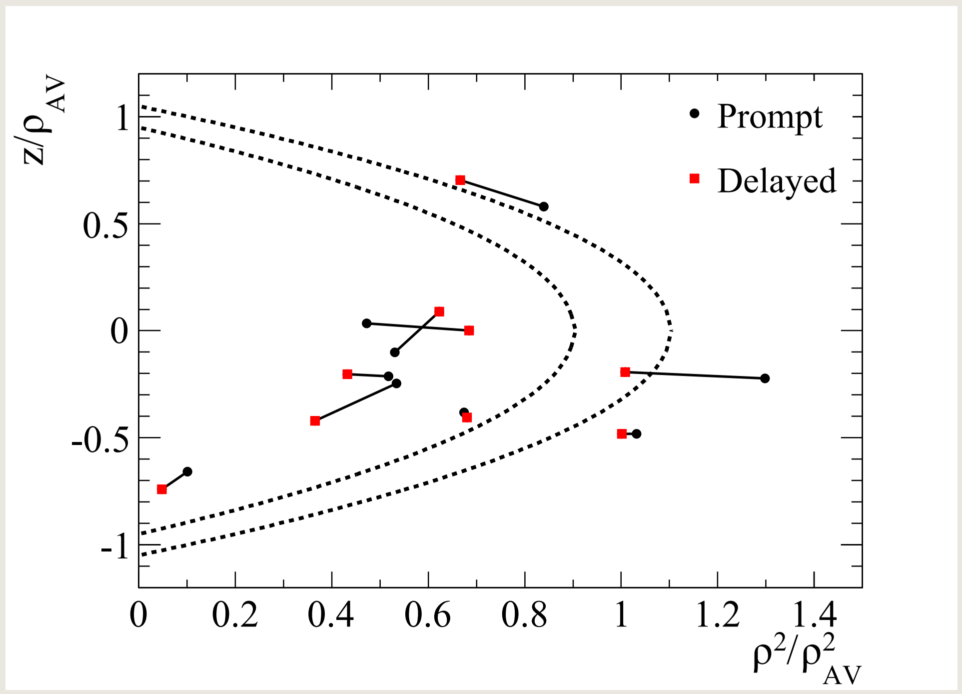
$$\sigma_H = 336.3^{+1.2}_{-1.5}\ \mathrm{mb}$$

Reactor Antineutrinos

→ Two independent analyses (Likelhiood / BDT).
→ 190 days of low-background data included.



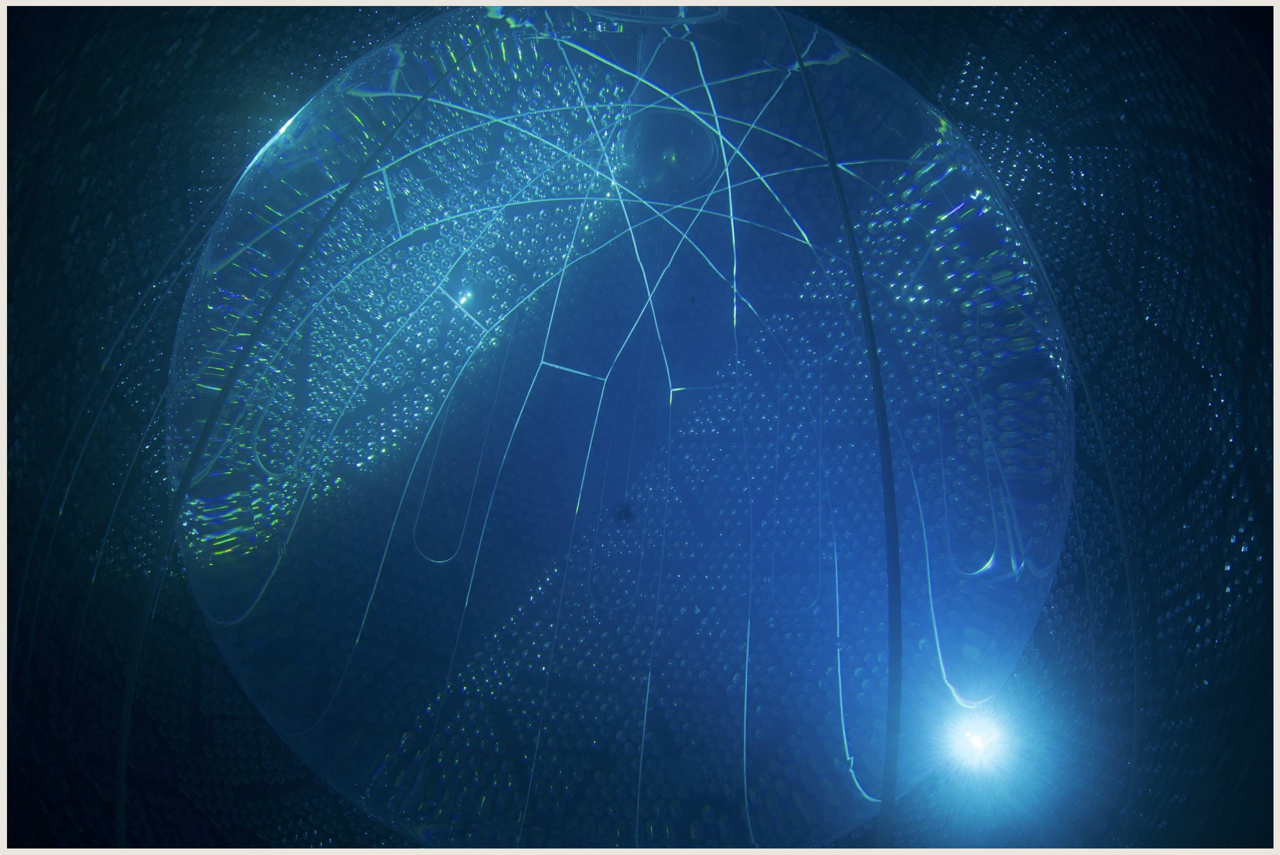
Phys. Rev. Lett. 130 (2023) 9, 9



Prompt/Delayed timing and position cuts along with a high neutron capture efficiency yielding a 3.5σ signal significance.

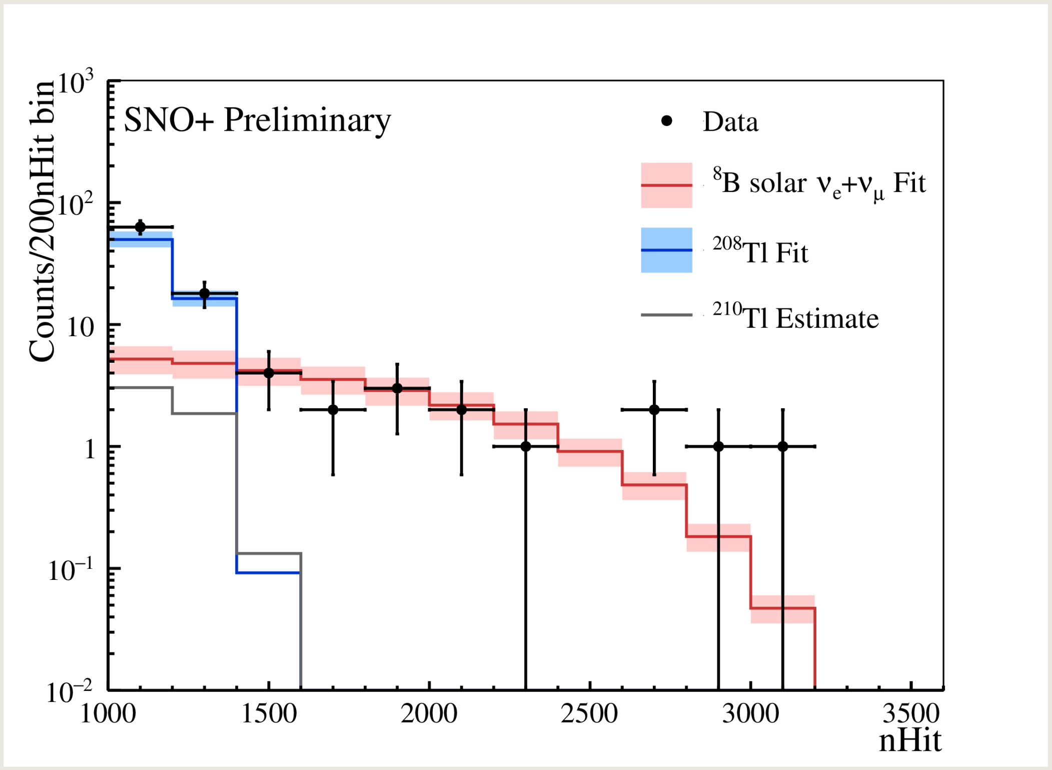
Scintillator Fill

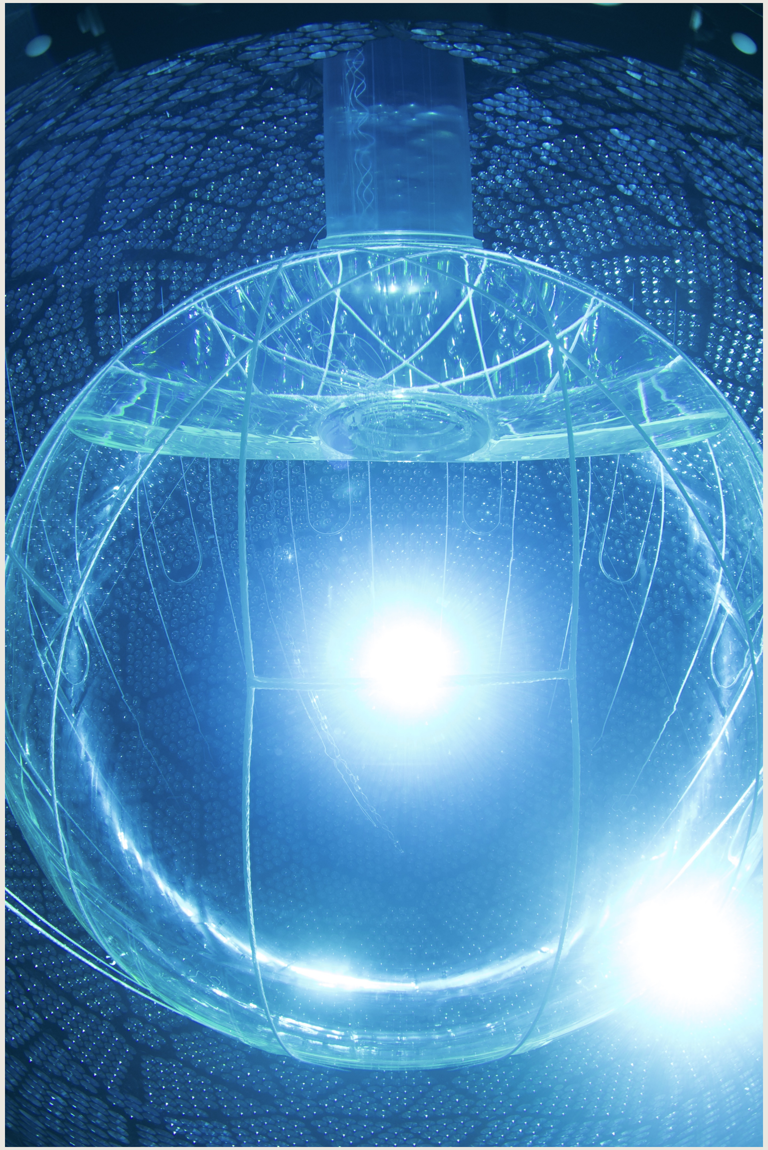
- → 780 tons of distilled LAB
- → loaded with ~2g PPO per liter LAB
- → Progressive filling phases provided opportunity for additional analyses with gradually increasing LAB quantity knd low PPO loading.
- → Solar neutrino, background, and directional reconstruction analyses performed.



Partial-fill results

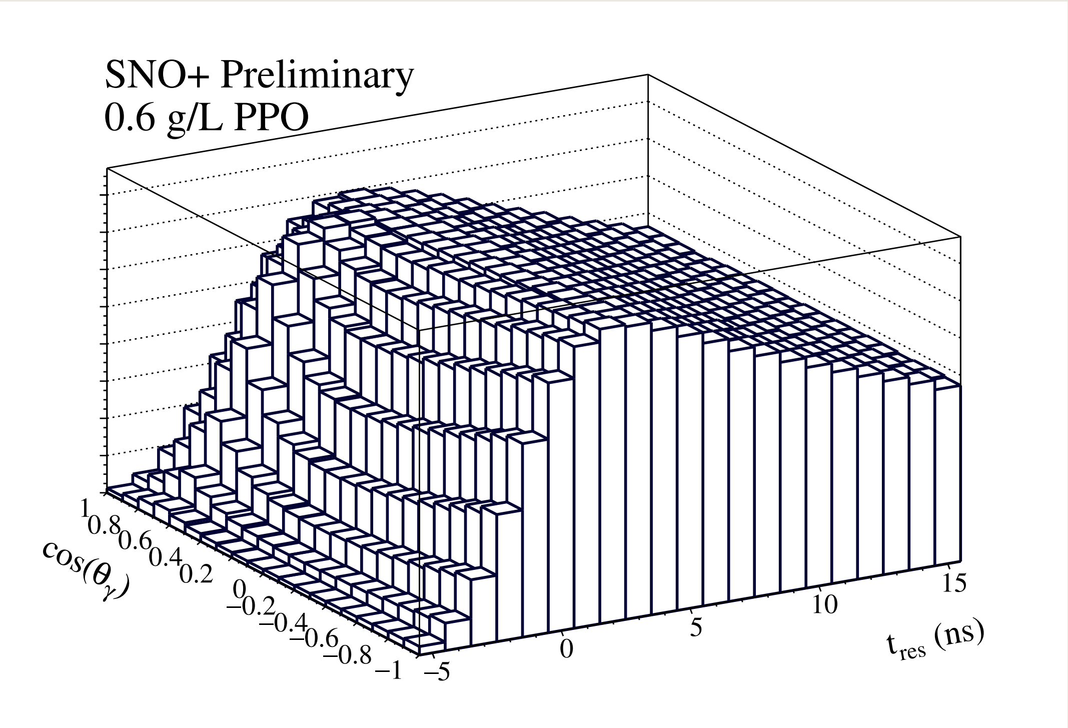
Extended filling phase provided opportunity to test analysis methods prior to completing the detector. This included measurements of various internal backgrounds as well as ^{8}B solar neutrinos.

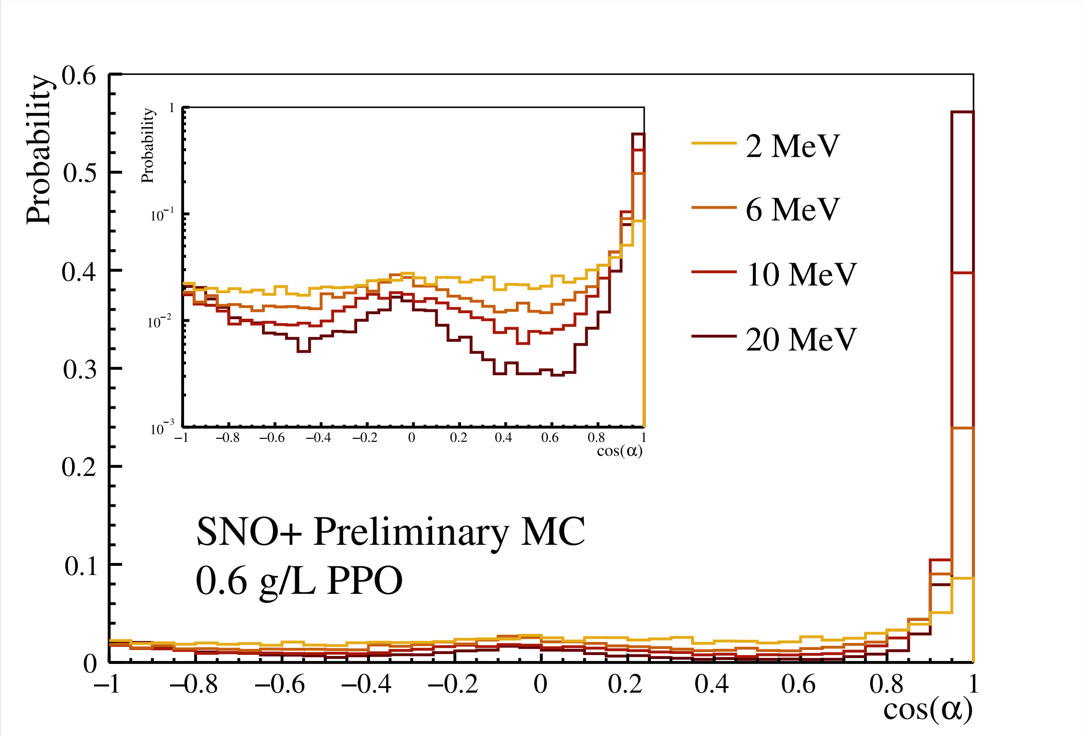




Directionality in scintillator

2D PDF in reconstructed time residuals and photon angle used to fit events direction.

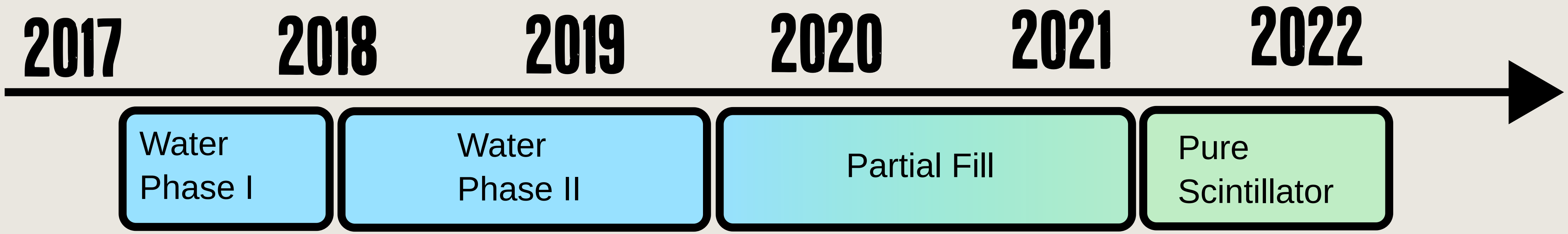




→ Preliminary simulations show that much of this information extends to full PPO loading.

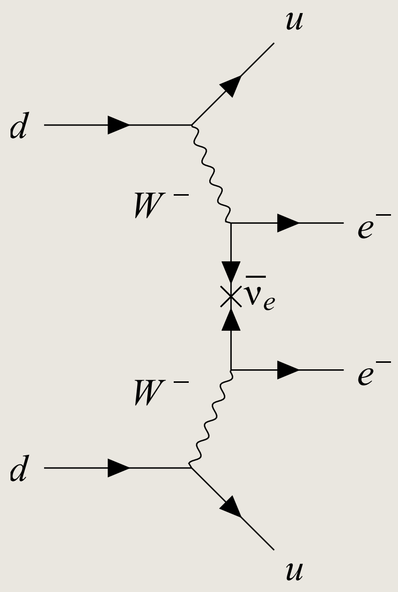
→ Potential use for background rejection (solar) and supernova pointing!

Status and Timeline

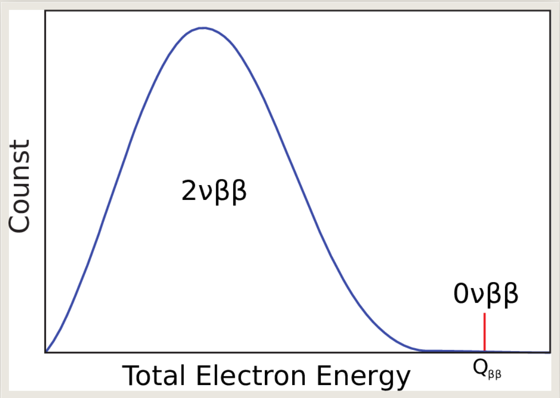


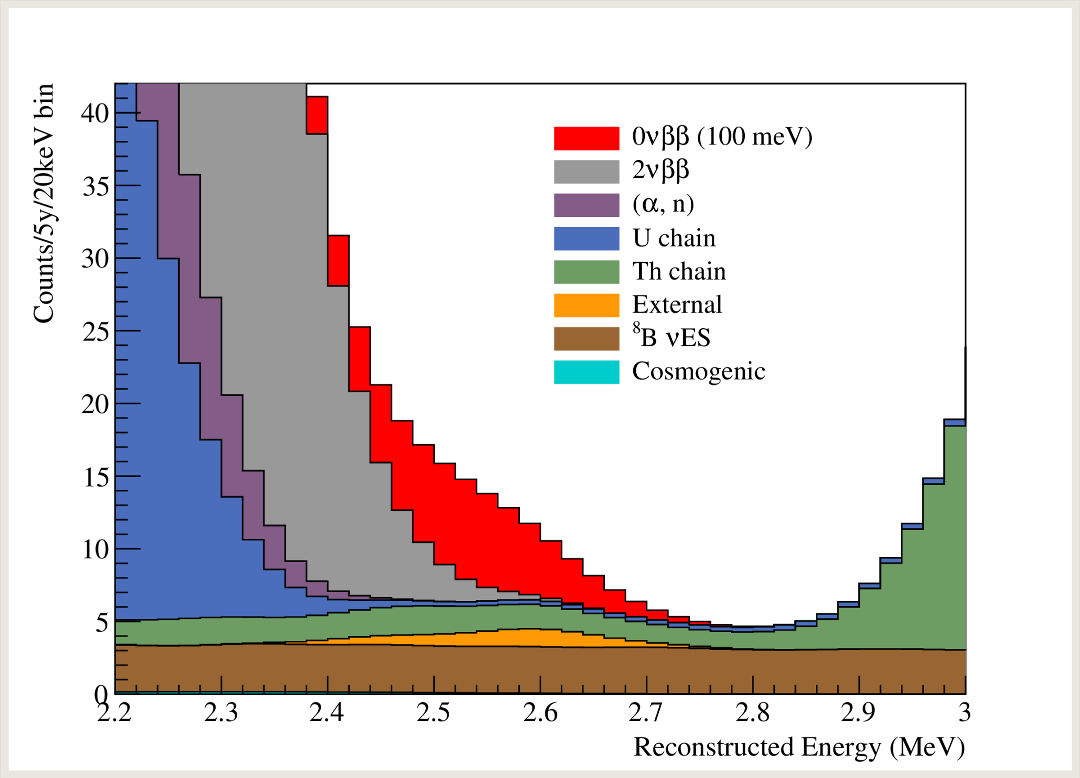
- Data from phase I and II water analyzed and published (new solar results in progress).
- Partial fill backgrounds analyzed to inform future analysis, understand the trigger system, and "practice" the final analysis.
- Detector is currently completely filled with liquid scintillator. PPO is still being incrementally added to hit the target concentration.
- Tellurium is expected to be mixed into the detector in 2024, following a stable scintillator phase.

Primary Physics: $0\nu\beta\beta$

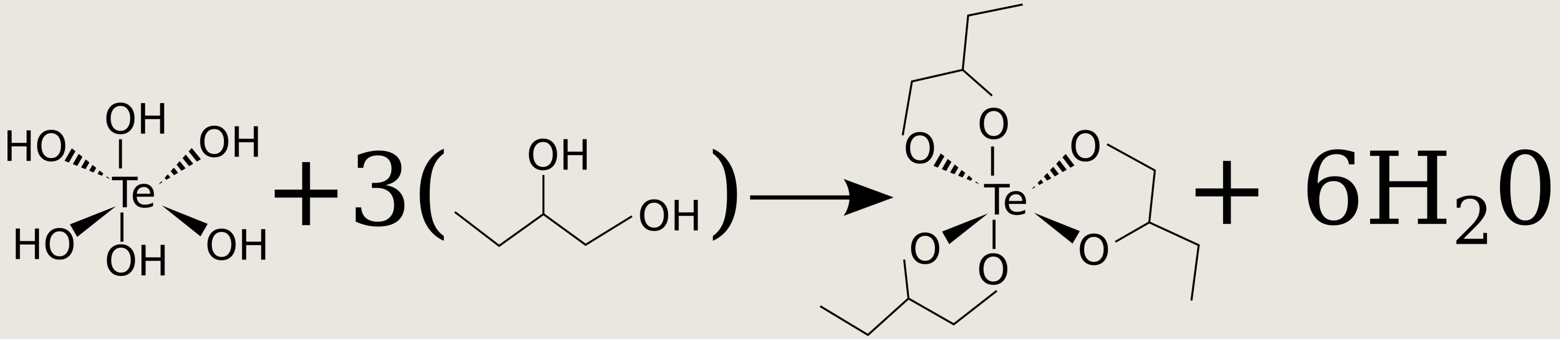


With a 2.6 MeV endpoint, the $0\nu\beta\beta$ signal sits in a region of well known backgrounds that can be supressed through fiducialization and constrained via sideband analyses.





Te-Loading



Telluric Acid Butanediol TeDiol

- → Scintillator consists of Linear alkyl benzene (LAB) + 2 g/l PPO.
- → Telluric acid dissolved into the scintillator using Butanediol.
- → High optical transparentcy and 50 times more light compared with water.
- → Plant is constructed and preparing to fill in 2024.

$0\nu\beta\beta$ Prospects

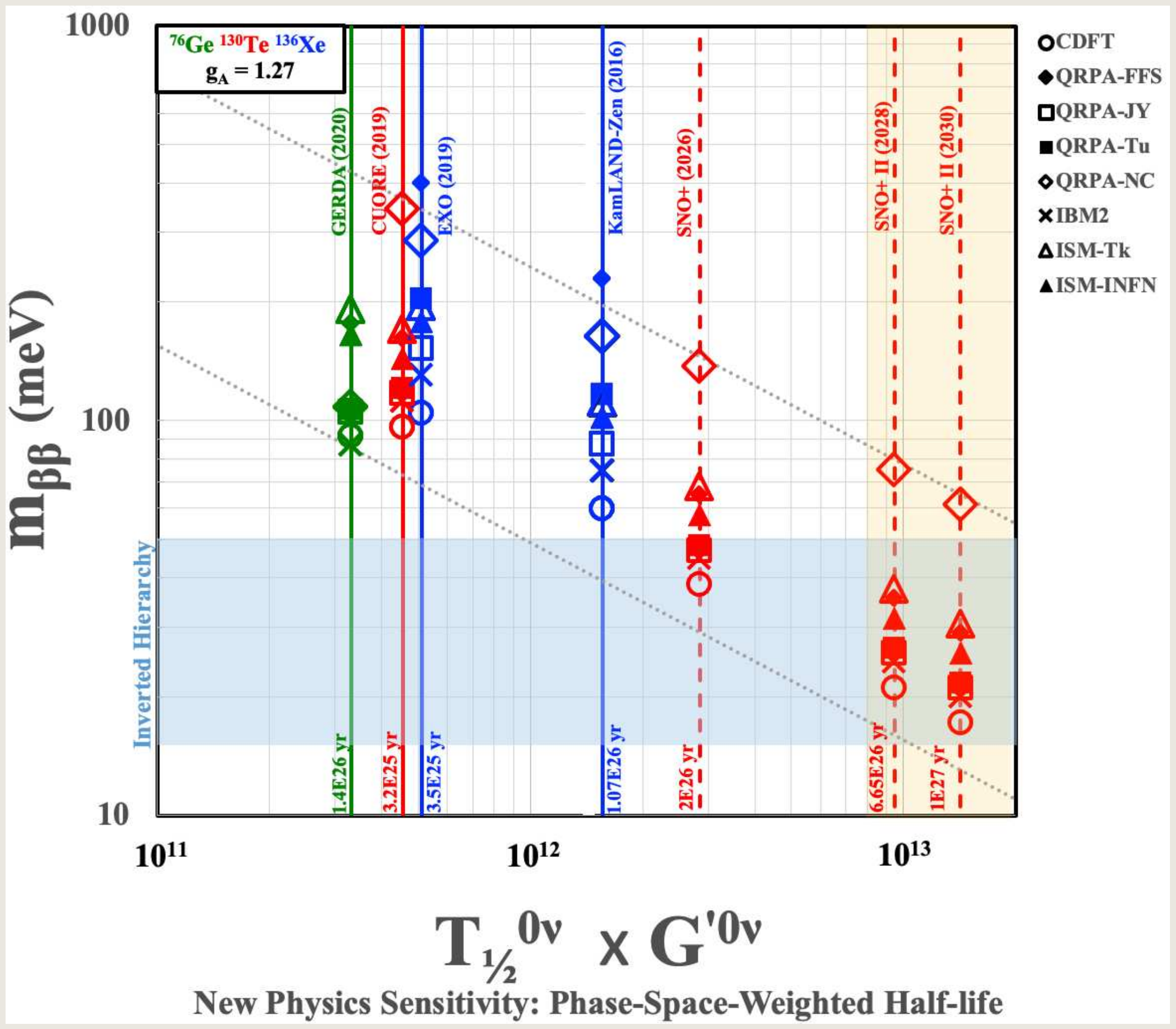
→ Counting analysis for 5 years in an optimized ROI:

- Expected half-life sensitivity $\tau > 2 \times 10^{26}$ years
- $m_{\beta\beta}$ range 37-89 meV (model dependent)

→ More detailed spectral analysis should further constrain backgrounds and improve the signal sensitivity

→ SNO+ technique is scalable

- Increased loading up to 3% with good light yield and stability
- Component upgrades



Solar Neutrino Program

Physics Program

→ ^{8}B energy spectrum

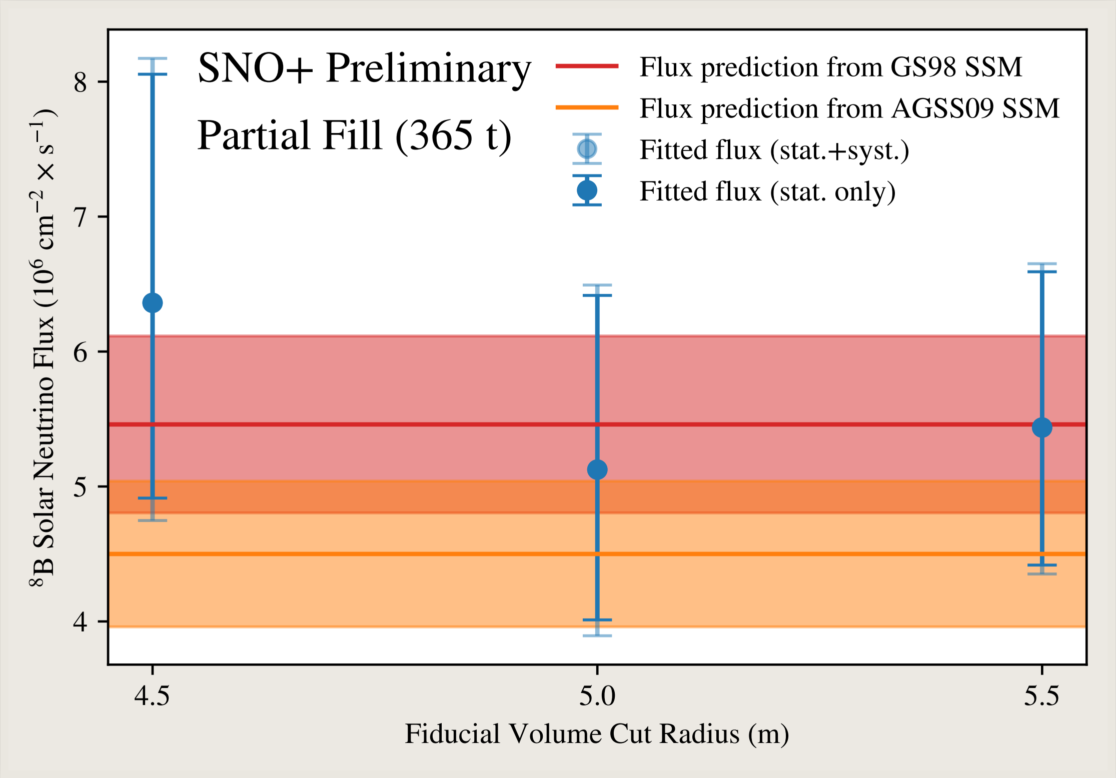
→ Low-energy flux (^{7}Be, *pep*, CNO)

→ Non-standard interactions

→ *hep* Search

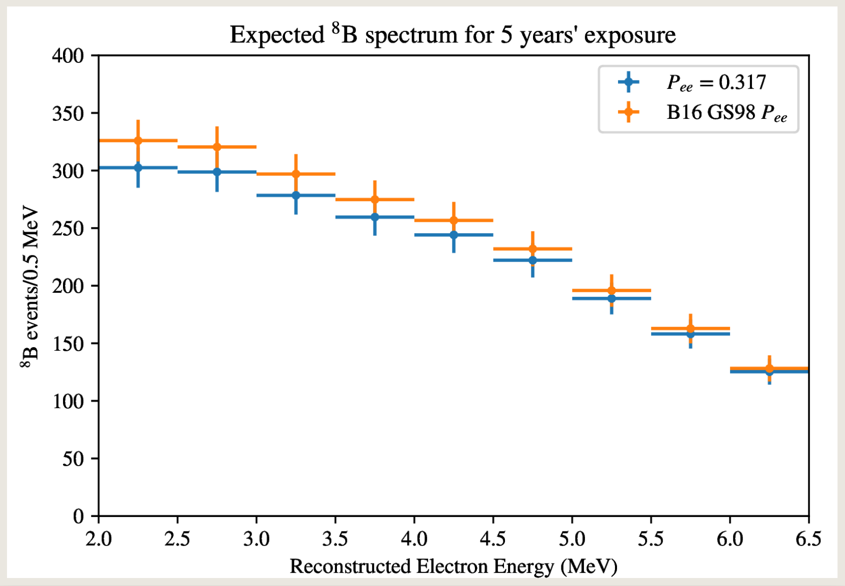
→ θ_{12} / Δm^2_{12} measurements

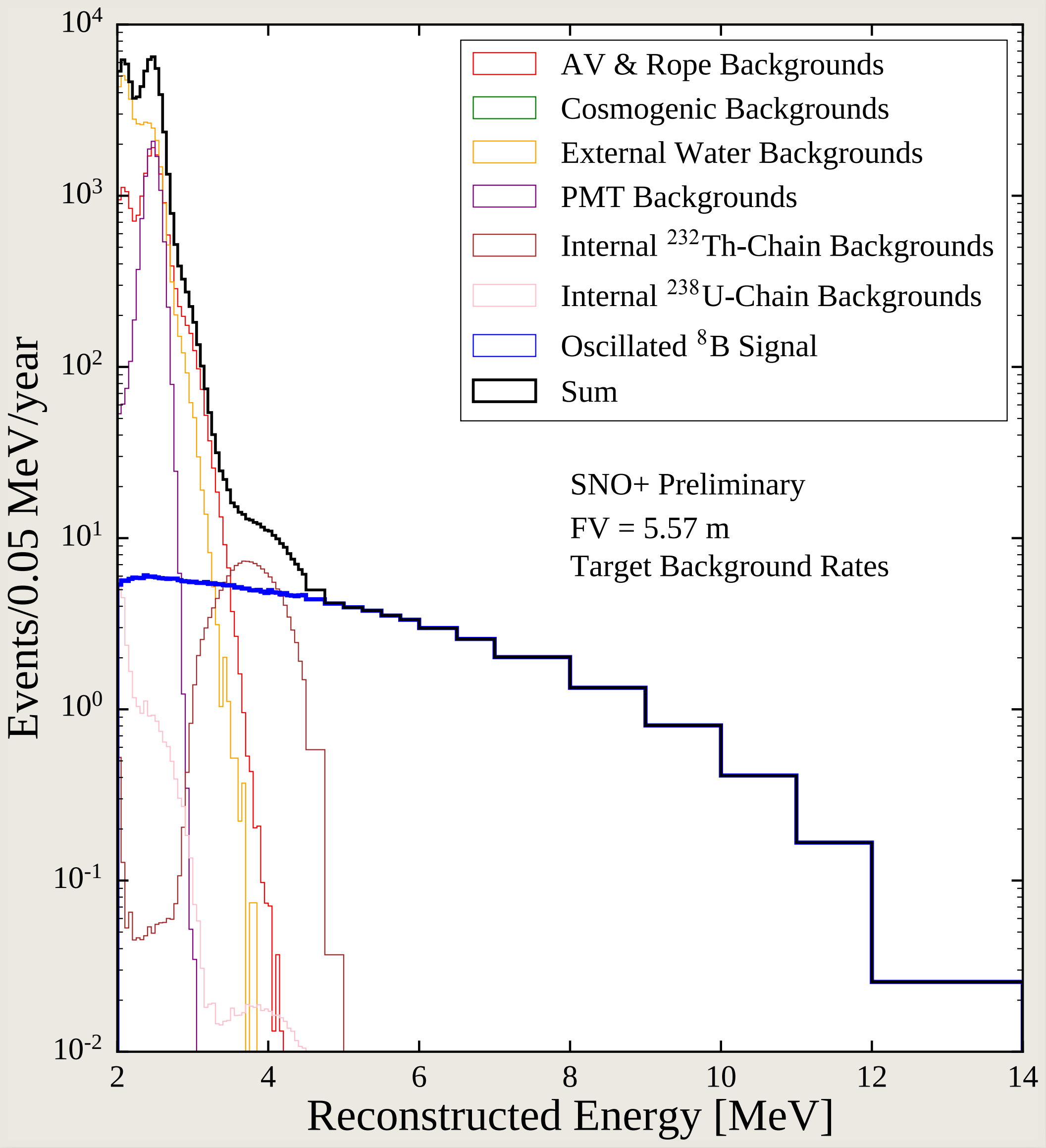
Measurements during partial-fill provide confidence in our scintillator models and reconstruction algorithms.



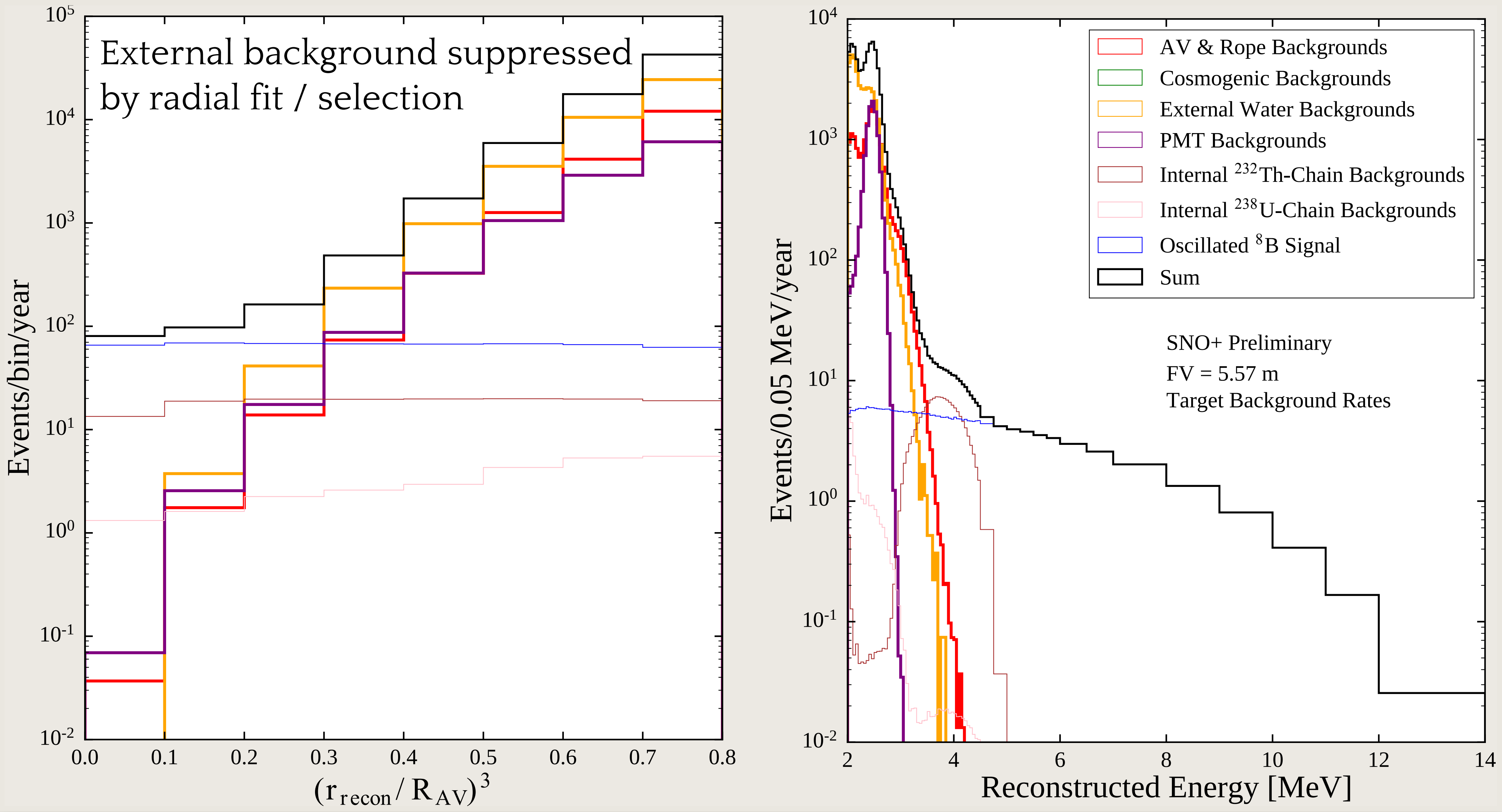
Solar ^{8}B Spectrum

- → Multiple analyses looking at the solar energy spectrum.
- → All analysis performed in 2D (energy, position) for background rejection.
- → Higher energy provides sensitivity to the ^{8}B spectrum shape and non-standard interactions.



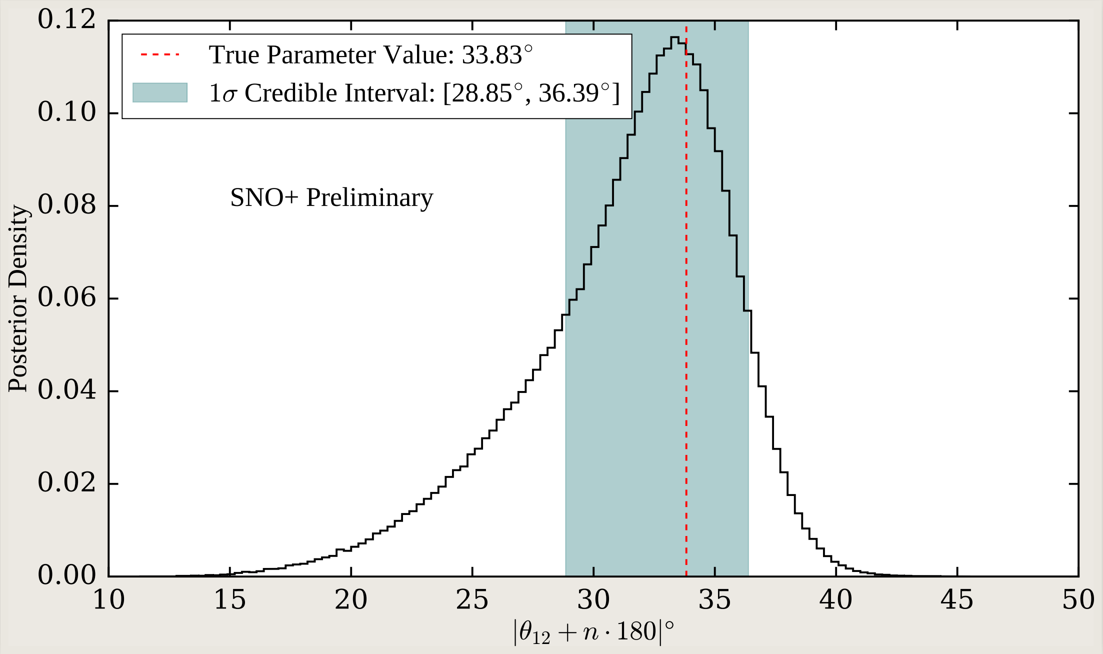


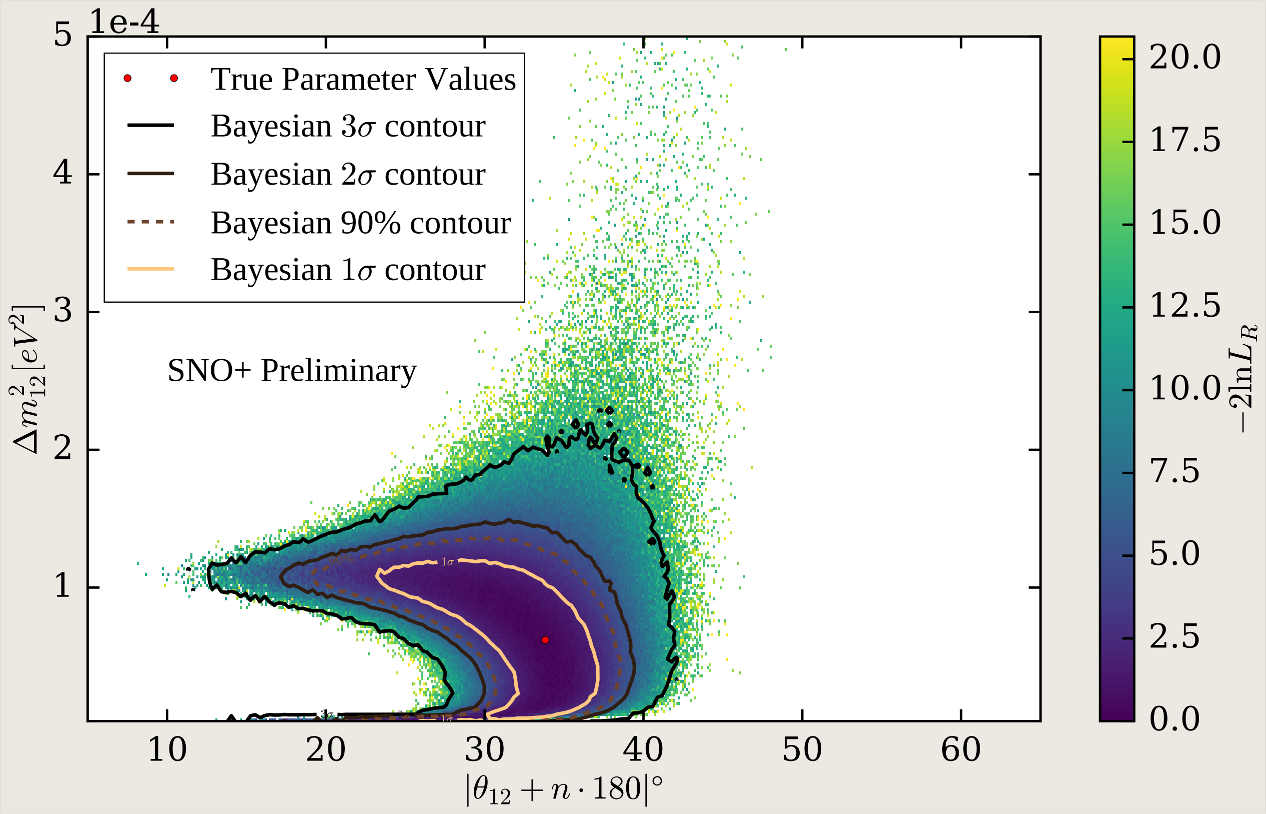
Solar ^{8}B Spectrum



Oscillation Analysis

- Fitting 2D PDFs in $Energy$ and $(Radius/Radius_{AV})^3$
- Oscillation parameters $(\theta_{12}, \Delta m^2_{12})$
- Solar flux and background levels constrainted through side-band and external measurements.



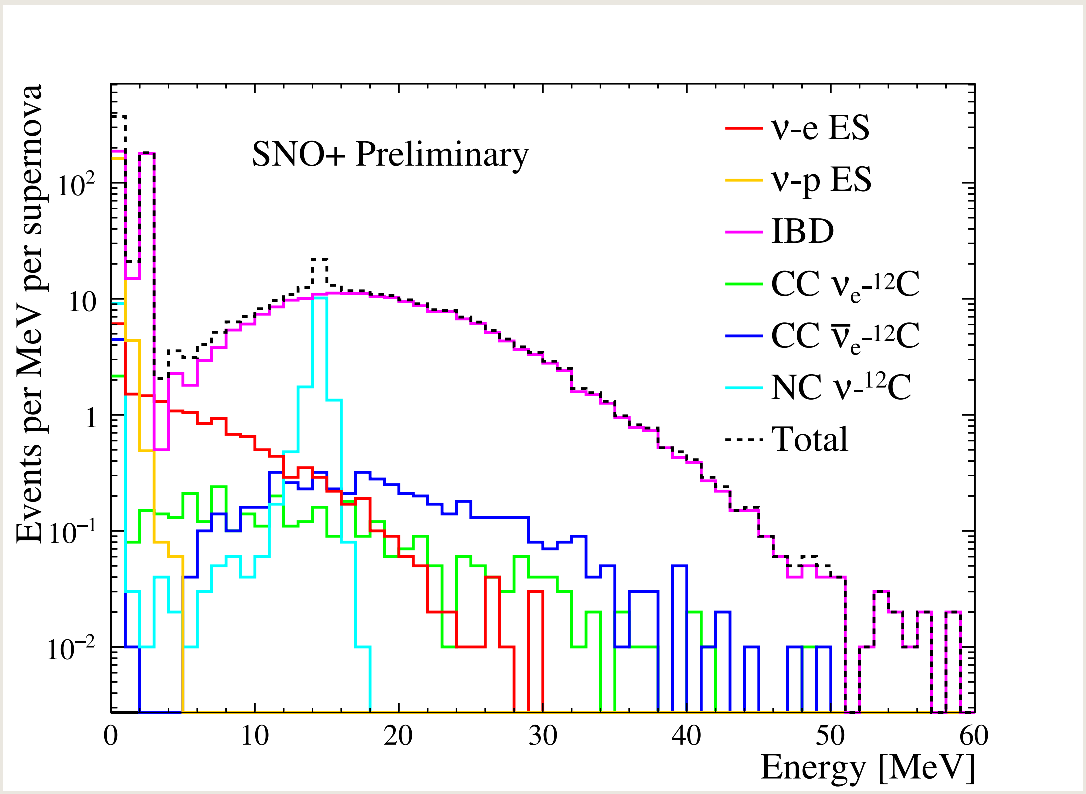


2D Posterior distribution of the oscillation parameters for 1 year of projected data using a Markov chain Monte Carlo.

Core-collapse supernovae

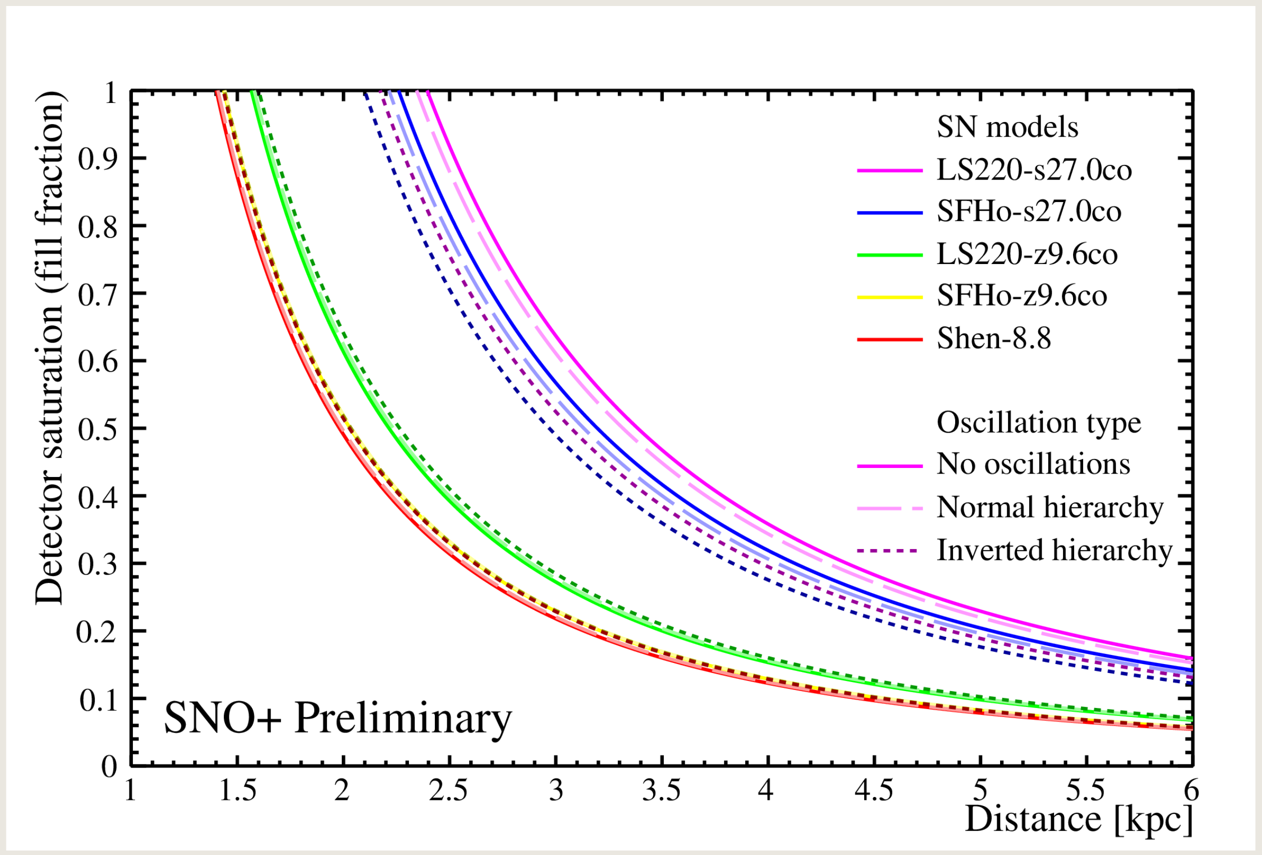
- → Reconstructed interaction energy.
- → Elastic scattering interaction (red) has potential for pointing within the new directional reconstruction in scintillator.
- → 27 $M_\odot$ at 10kpc, no oscillation

IBD	194.7 ± 1.0
NC ^{12}C	43.8 ± 8.7
ν-e ES	~ 13
ν-p ES	$118.9 \pm 3.4\ (E > 200\mathrm{kev})$



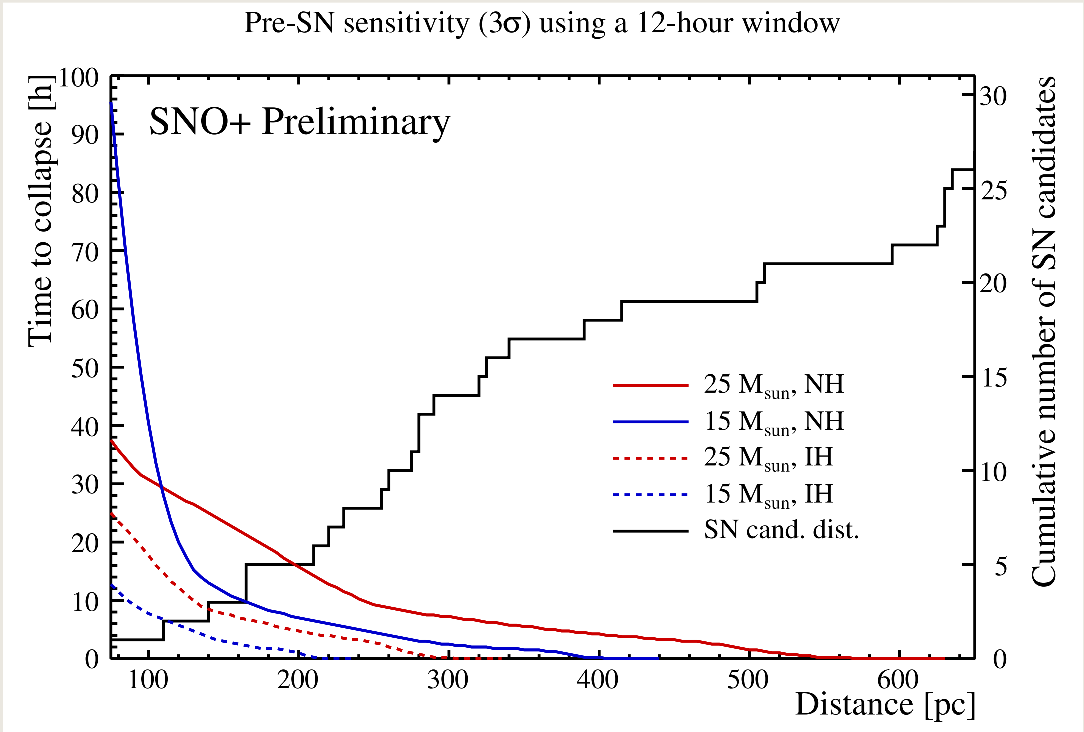
Burst trigger sensitivity -> SNEWS

- → Burst trigger designed for real-time alarming (for SNEWS).
- → 1-2s latency and ~30s analysis.
- → Dedicated supernova shifters at all times.
- → Sending "test" alarms to SNEWS since 2022 in preparation to begin sending alarms to SNEWS2 this year.



Pre-supernova neutrino monitoring

- → Sensitivity based on an increase of IBD-like coincidence events.
- → Signal efficiency: 86.3% (coincidence) x 91% (prompt energy) $\longrightarrow$ 78.5%.
- → Detection over a 12-hour rolling window.
- → Signal to SNEWS should be the combined statistical significance across all experiments.



Sensitivity shown for 110 reactor, 25 geo, and 275 (α, n) events / year.

Conclusion

Snoplus is full of liquid scintillator and is in the process of fully doping with Tellurium.

Analyses and measurements in the water and partial fill phase will be used to inform future results.

Scintillator and Tellurium phases provide opportunities for **Solar** and **Supernova** neutrino measurements.