SNO+: Progress and Prospects

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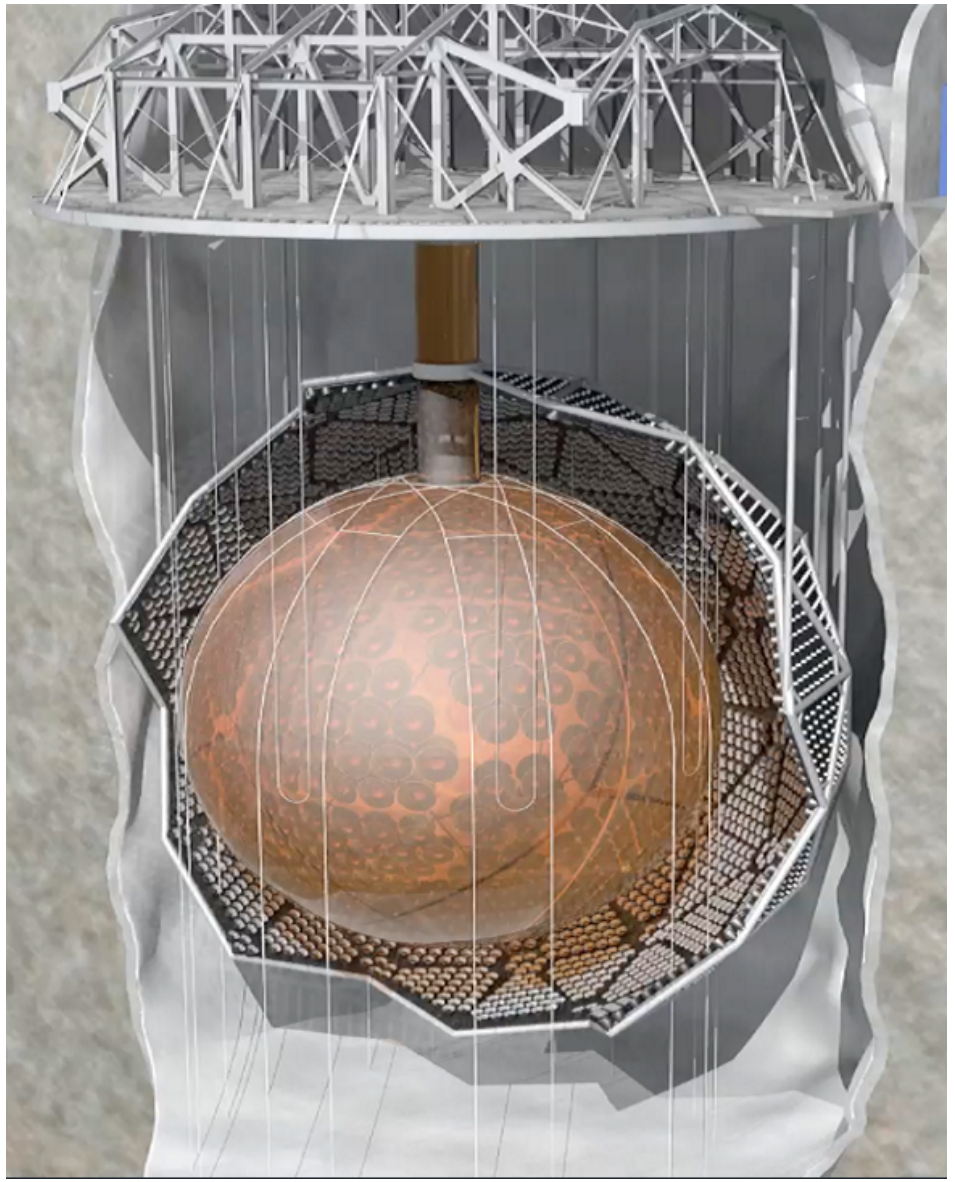
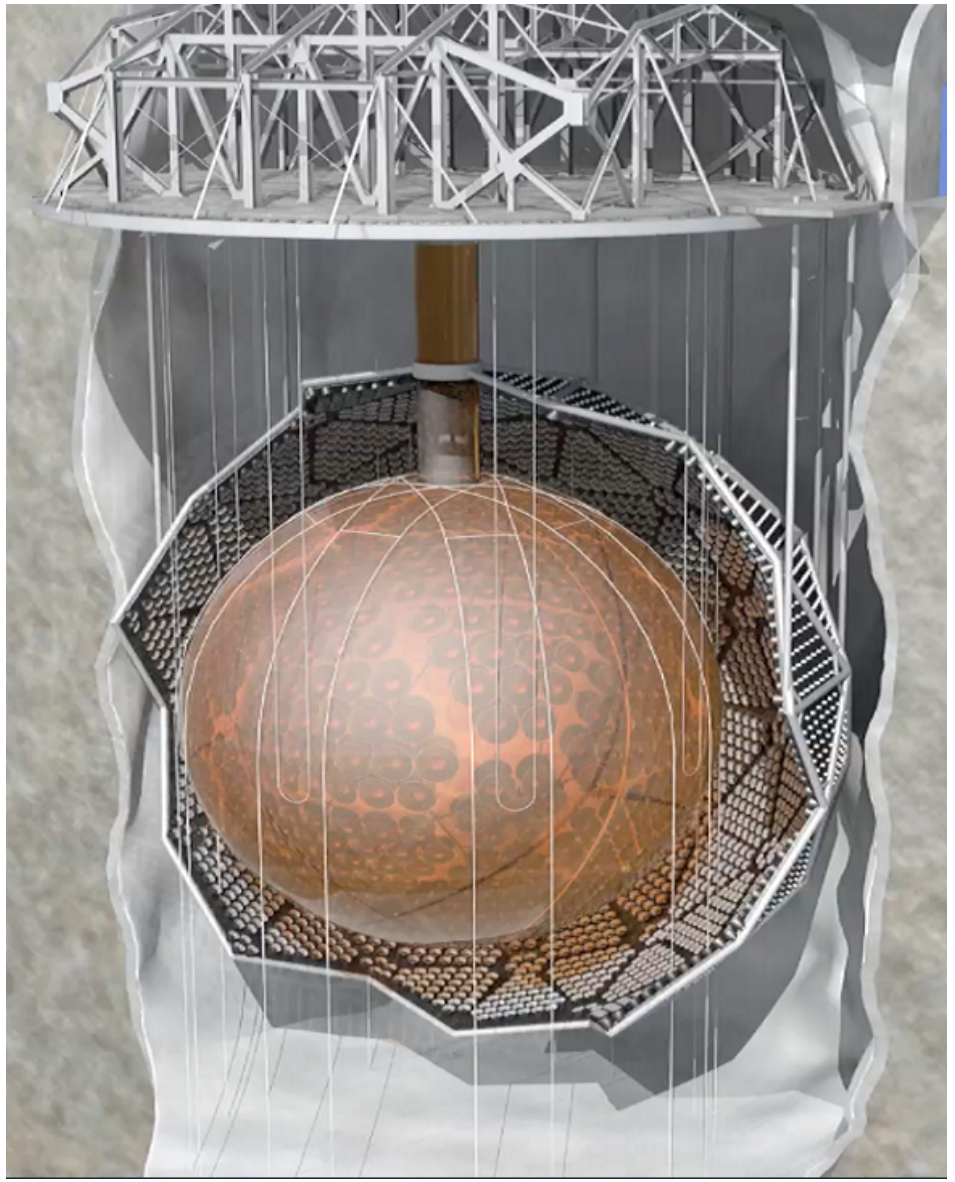
Introduction to SNO+

- SNO+ is a multipurpose neutrino detector
  - Primary mission: $0\nu\beta\beta$
  - Additional measurements
    - ★ **Solar**,
    - ★ **Reactor**,
    - ★ **Geo**,
    - ★ **Supernova**
- Sensitive to
  - $\nu_e + e^- \rightarrow e^- + \nu_e$
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Other channels...



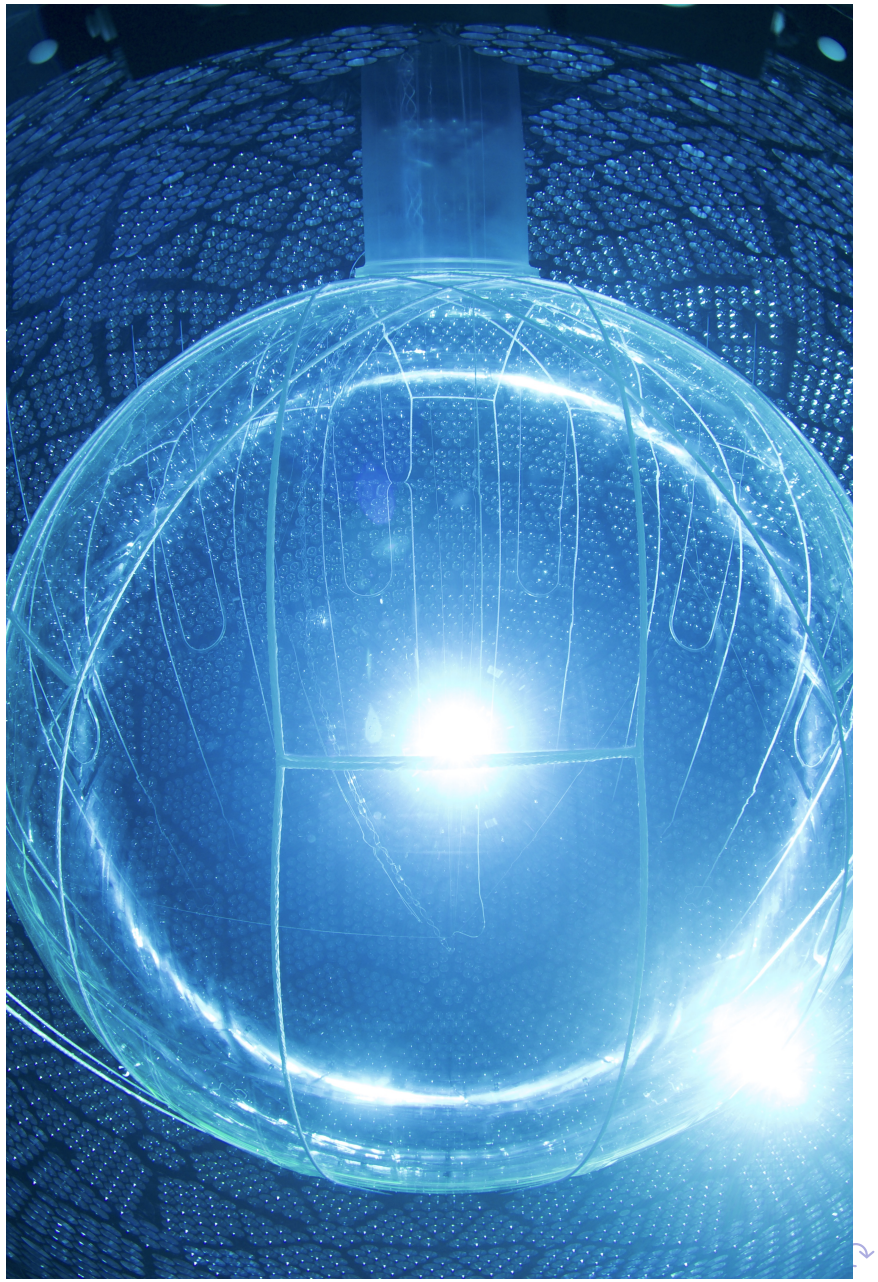
The SNO+ Detector

- JINST 16 P08059
- 2 km underground
- 12 m diameter acrylic vessel
  - 780 tonnes liquid scintillator
- 9362 inward facing PMTs
- $\approx$ 17 m diameter geodesic support structure
- UPW shielding fills surrounding cavity (external veto)



Filling History

- May 2017; Water fill complete: Start water data collection
- July 2019; Started replacing 908 t of UPW with LAB;
- March 2020 to Oct 2020:
  - Fill paused for pandemic (364 t)
- Fill Completed April 2021
- Added PPO to April 2022
- BisMSB added July to Dec 2023



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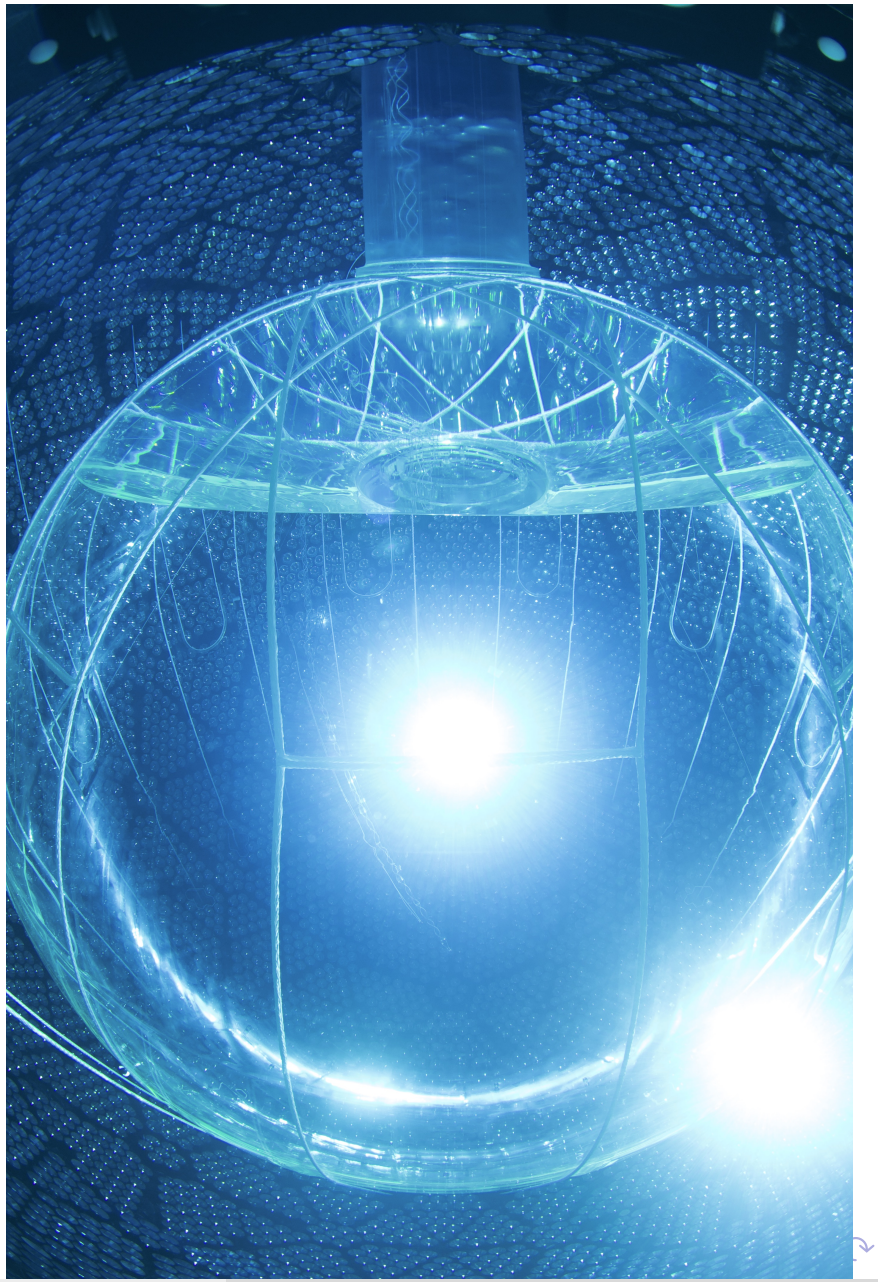

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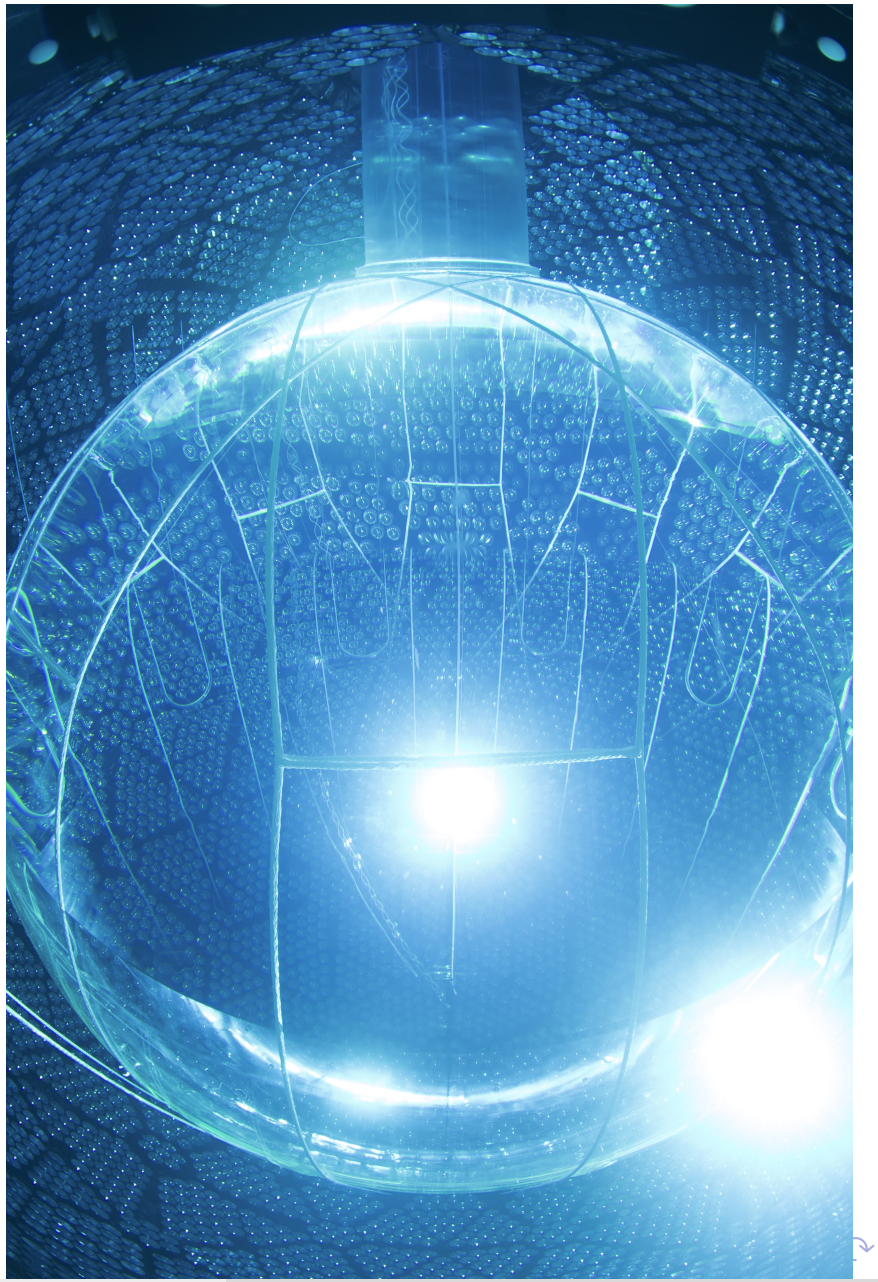

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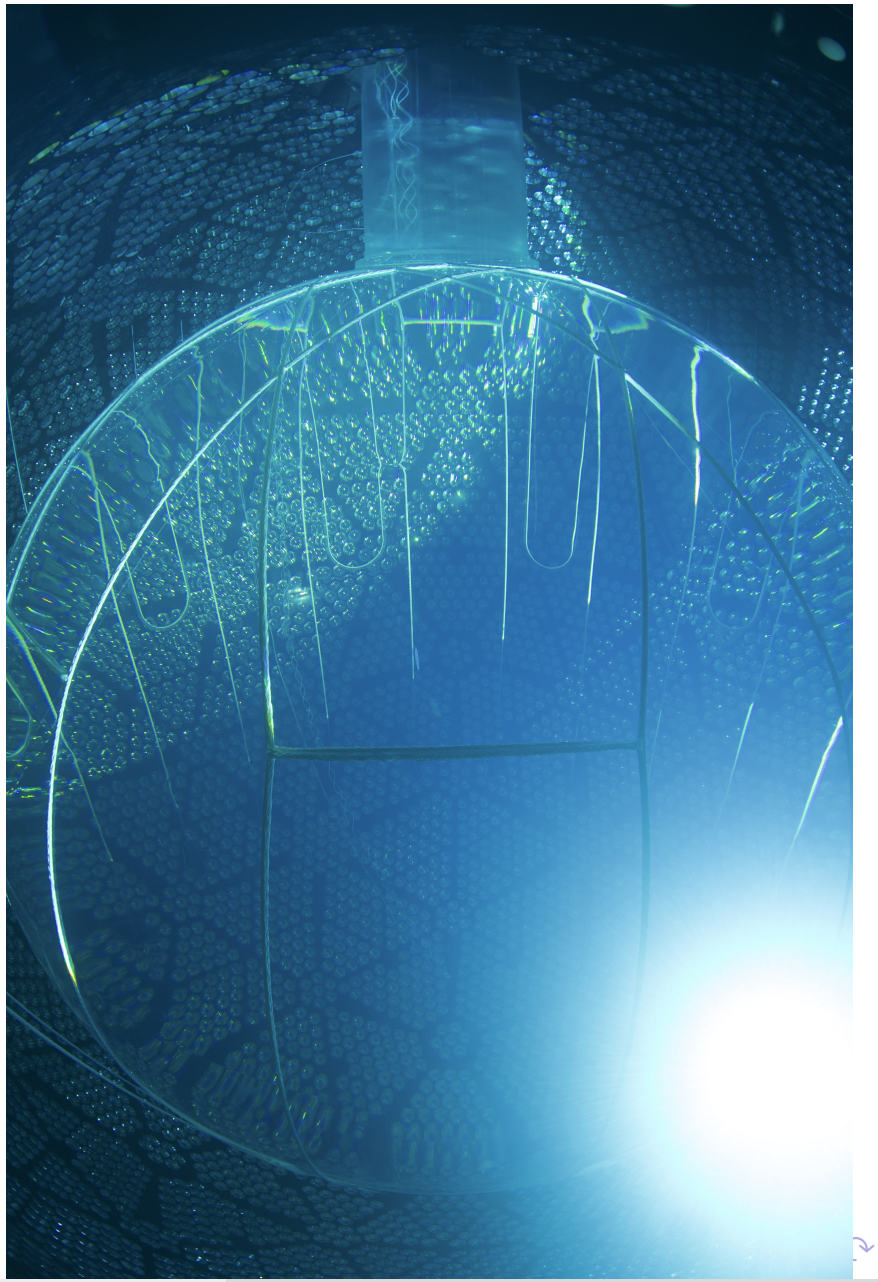
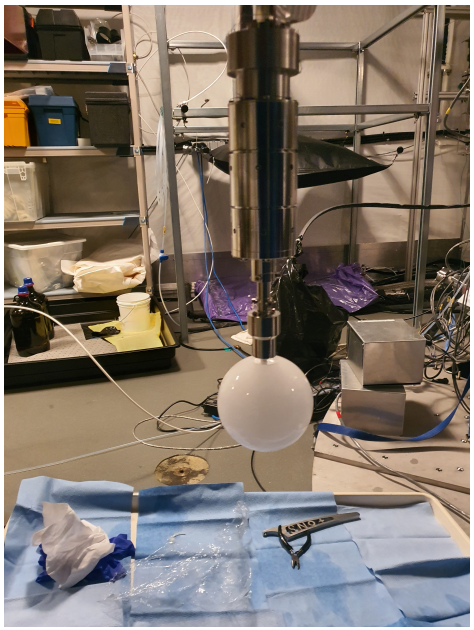
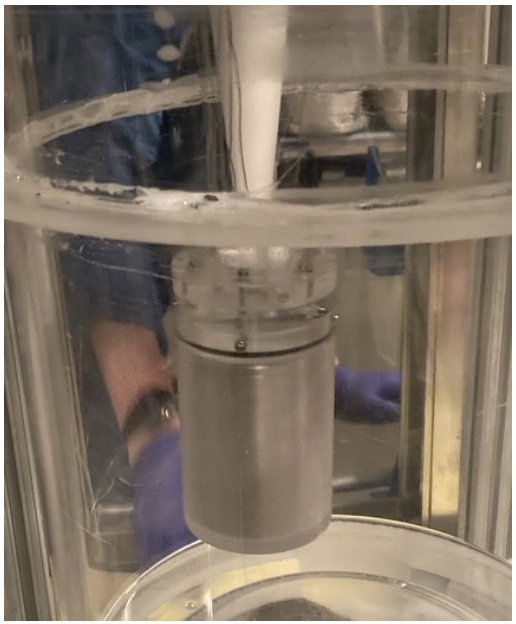
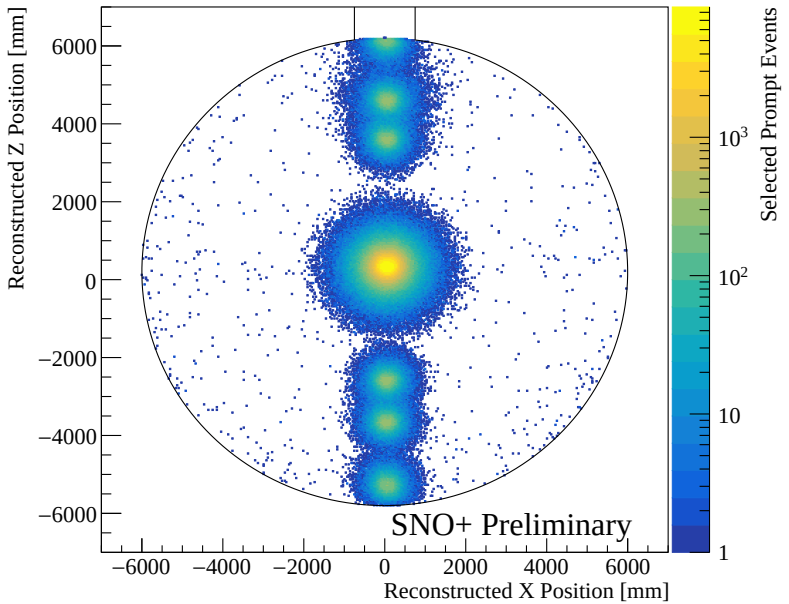


Calibration Systems

- Compatible with Scintillator
- Suppress radon incursion
- Now online: deployed sources in addition to embedded systems
- Optical sources
- AmBe source

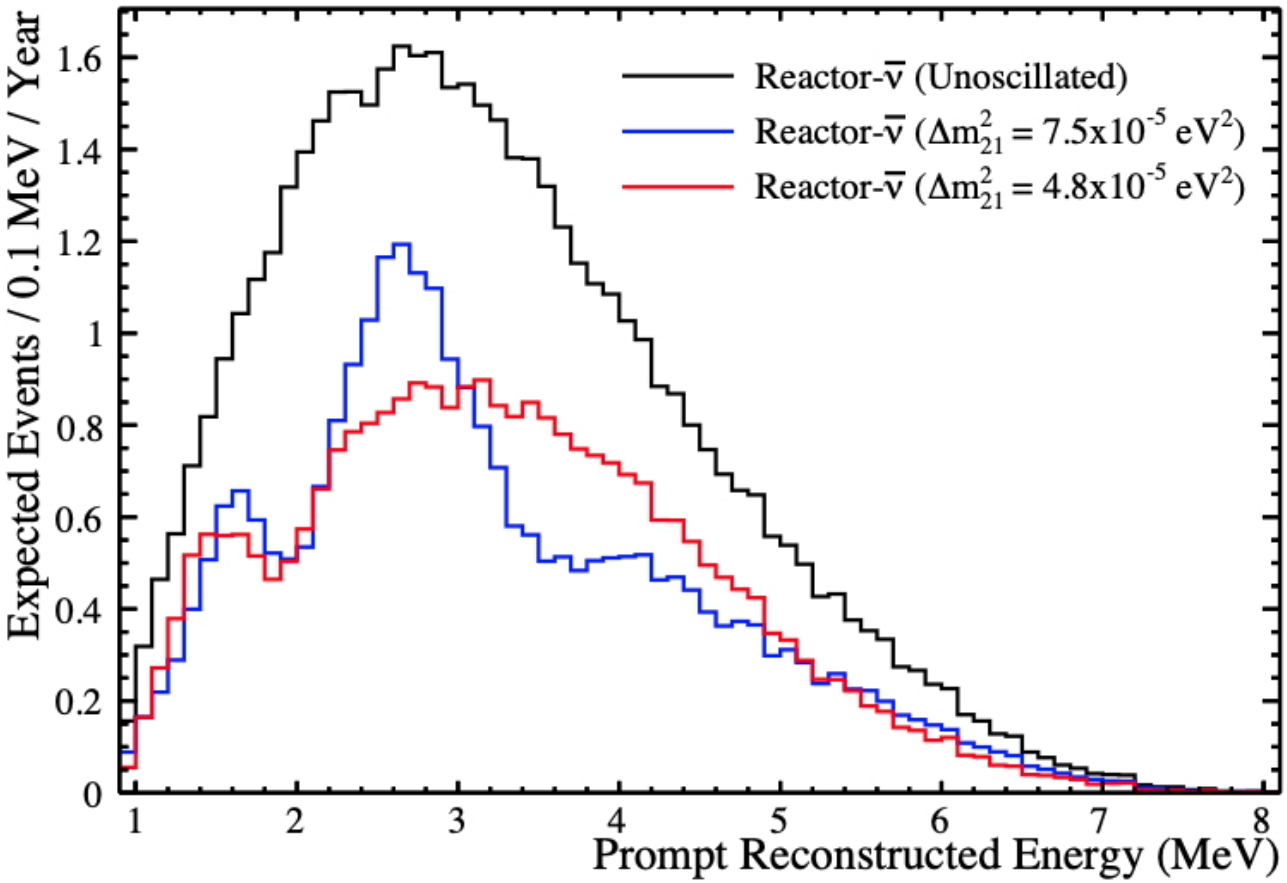




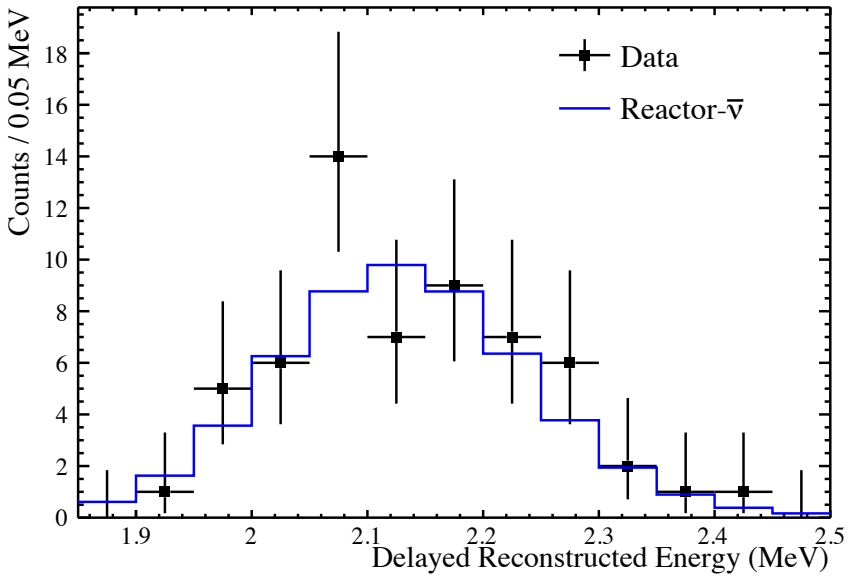


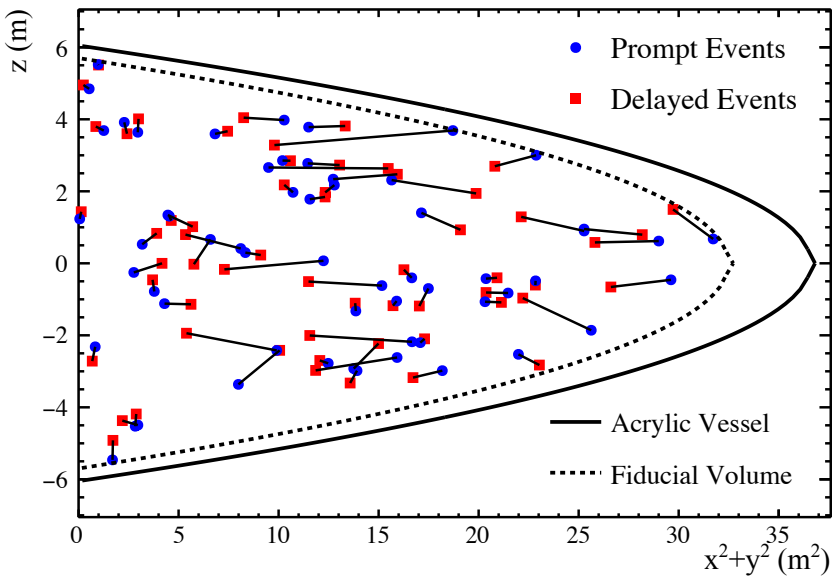
Anti-Neutrino Spectrum in SNO+

- 2×10^{20} $\bar{\nu}$ per second per GW of thermal power
- CANDU reactor rates estimated from hourly IESO data
- Other reactor rates estimated from IAEA monthly averages



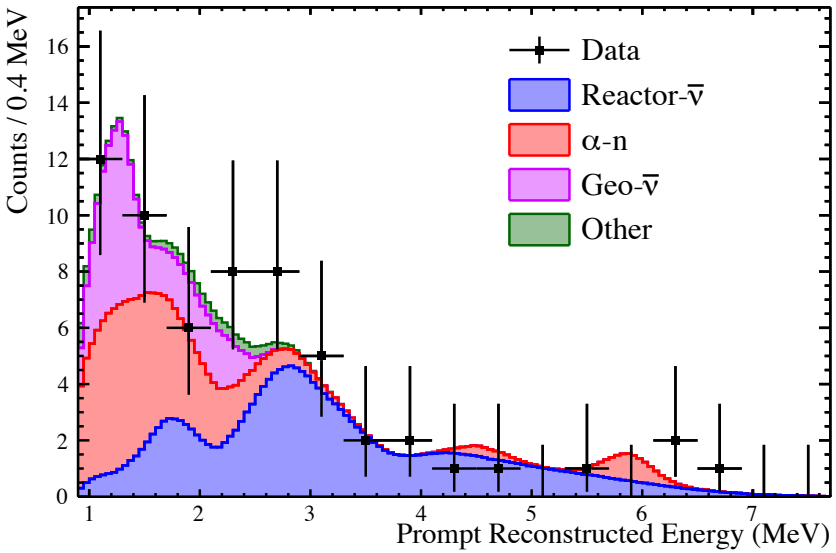
Reactor $\bar{\nu}$ in Full Scintillator Detector

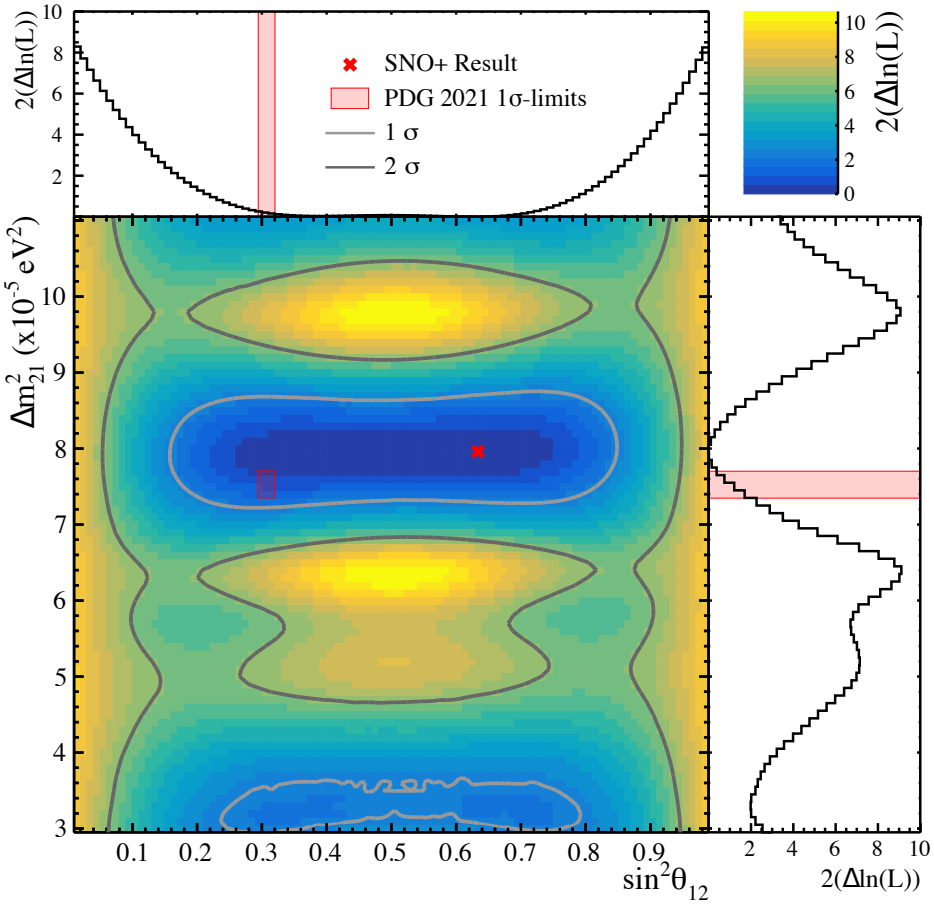




- Used data collected between April 2022 - March 2023
  - Stable running period following PPO addition
- Reduced (α, n) specific activity
  - ^{210}Po decays with 138 day half-life
  - Improved senstitivity compared to partial-fill $\bar{\nu}$ analysis
  - Eur Phys J C 85, 17 (2025).

Oscillation Measurements



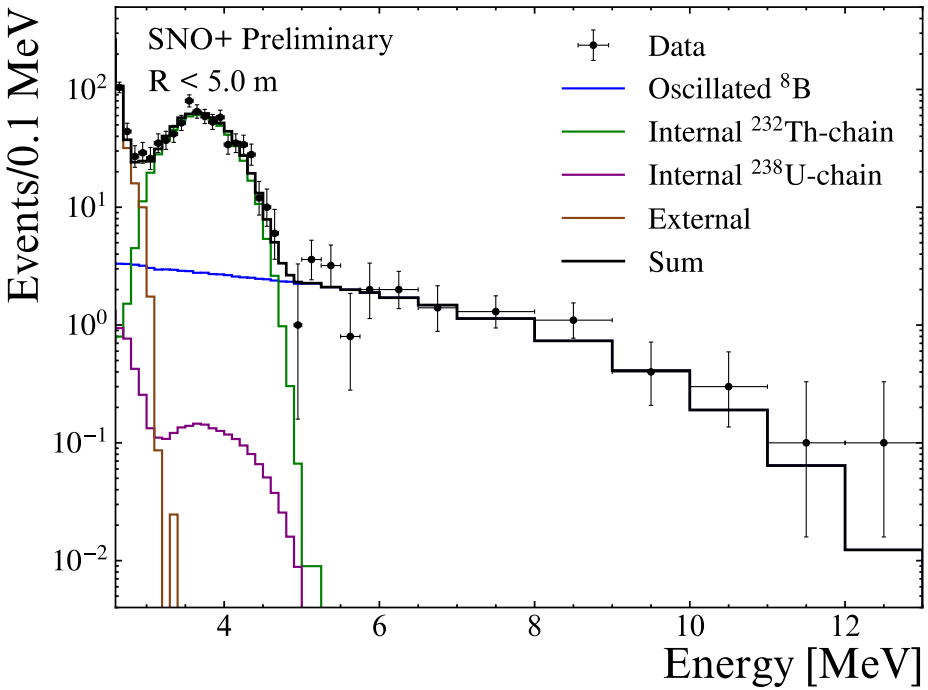


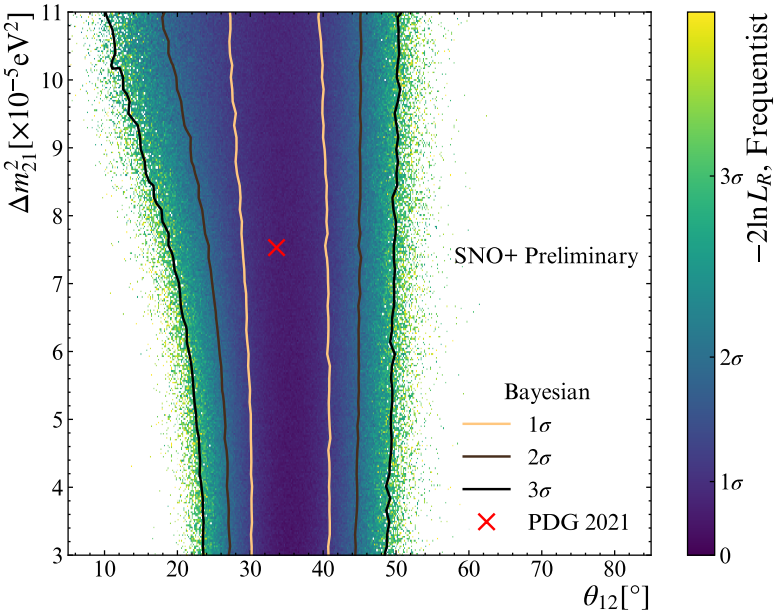
- Phys Rev Lett 135, 121801

- Allows $\Delta m^2_{12}, \sin^2 2\theta_{12}$ fit
- Best fit at $\Delta m^2_{12} = (7.96^{+0.48}_{-0.42}) \times 10^{-5}$ eV^2

Solar Neutrino Measurements In Scintillator

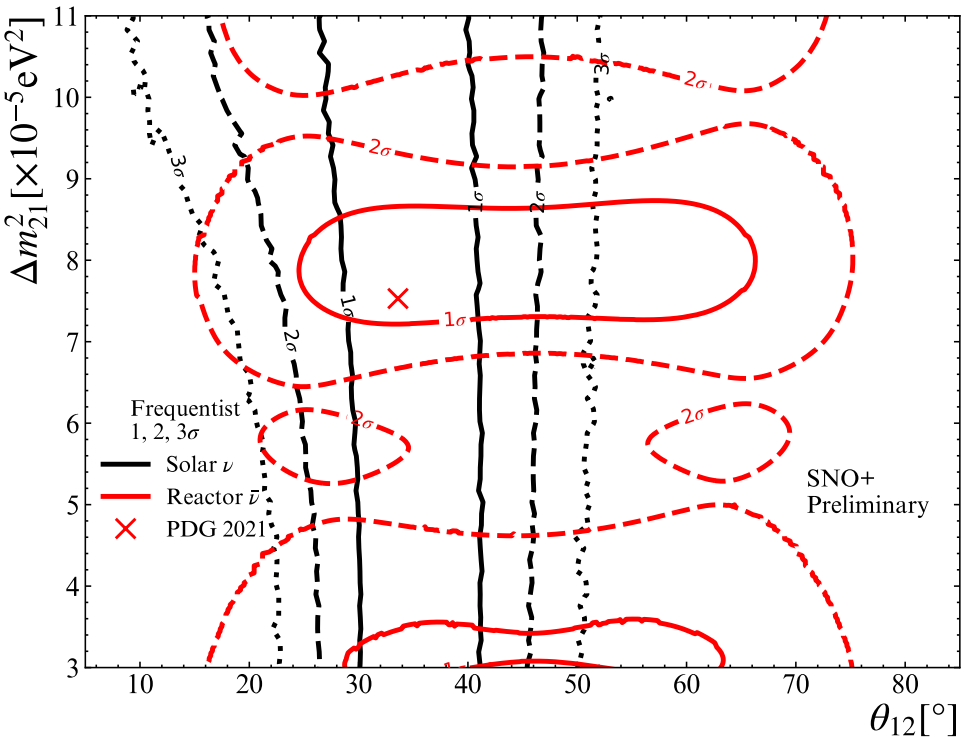
- Measurement of solar neutrinos in progress
- Elastic electron-neutrino scattering signal





- Complementary oscillation measurement
  - More sensitive to θ_{12}

Combination with of Reactor and Solar neutrino results



- Adding solar data better constrains θ_{12} in addition to Δm^2_{12}
- Ease tension in measurements to be consistent with KAMLAND
  - KAMLAND + global solar $\Delta m^2_{12} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
  - **But:** SK+SNO global solar $\Delta m^2_{12} = (4.8^{+1.3}_{-0.6}) \times 10^{-5}$ eV^2

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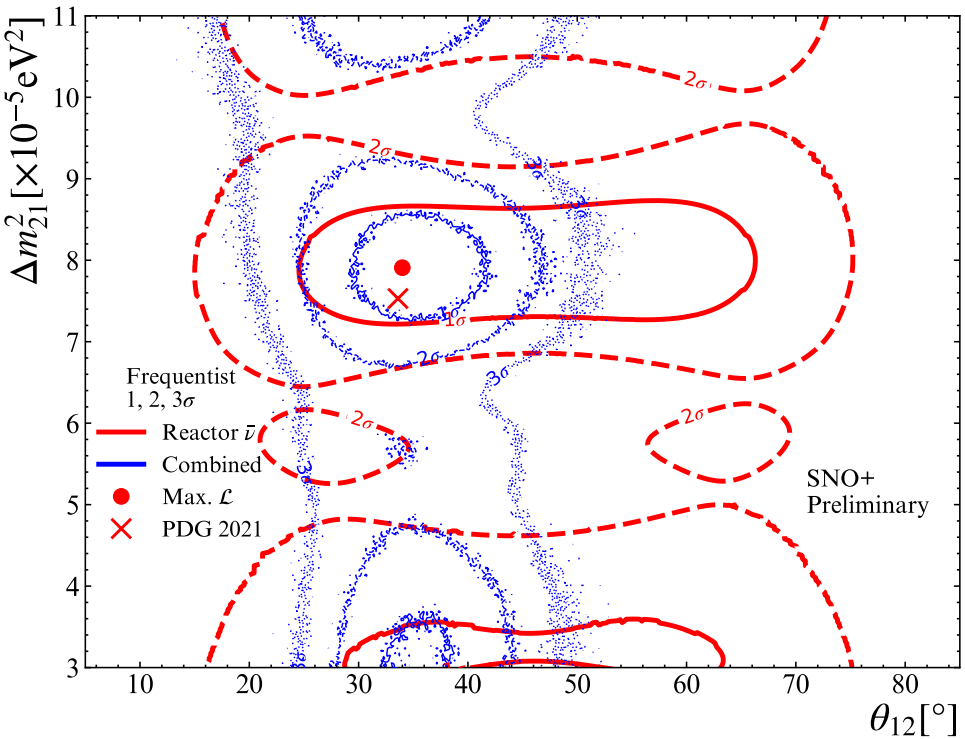

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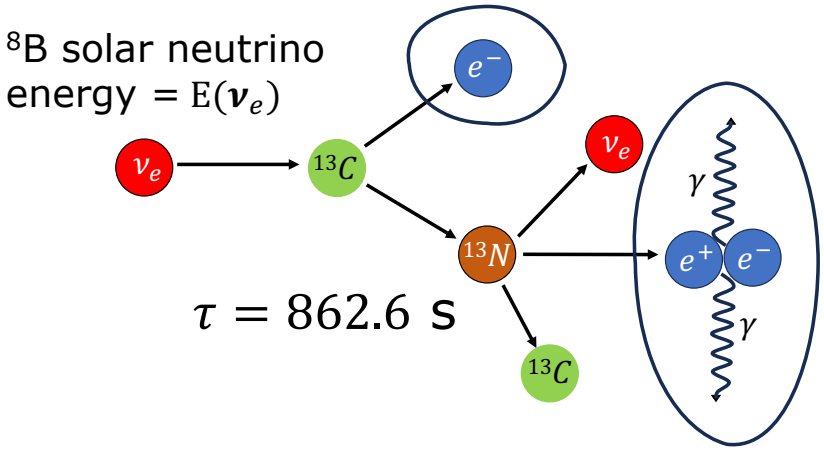
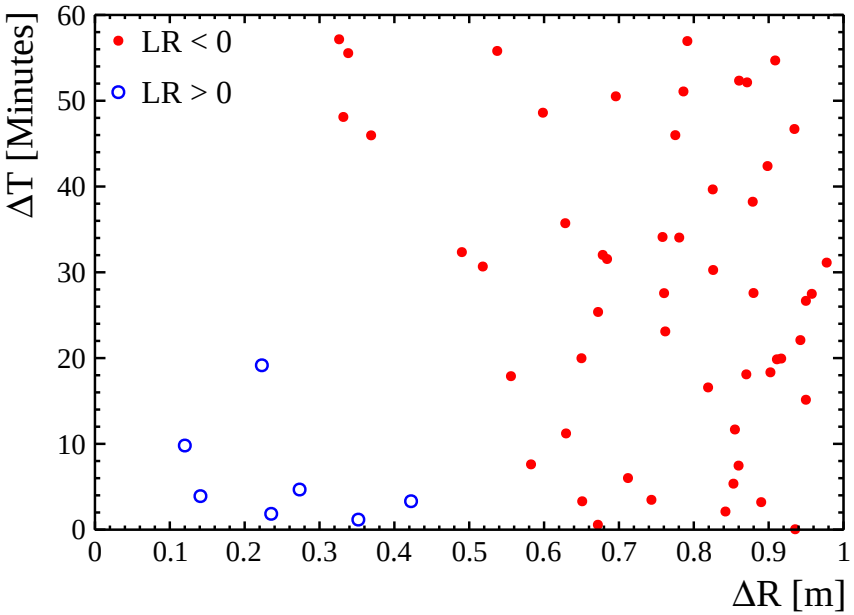
CC Interactions between ^{13}C and ^{8}B Solar Neutrinos

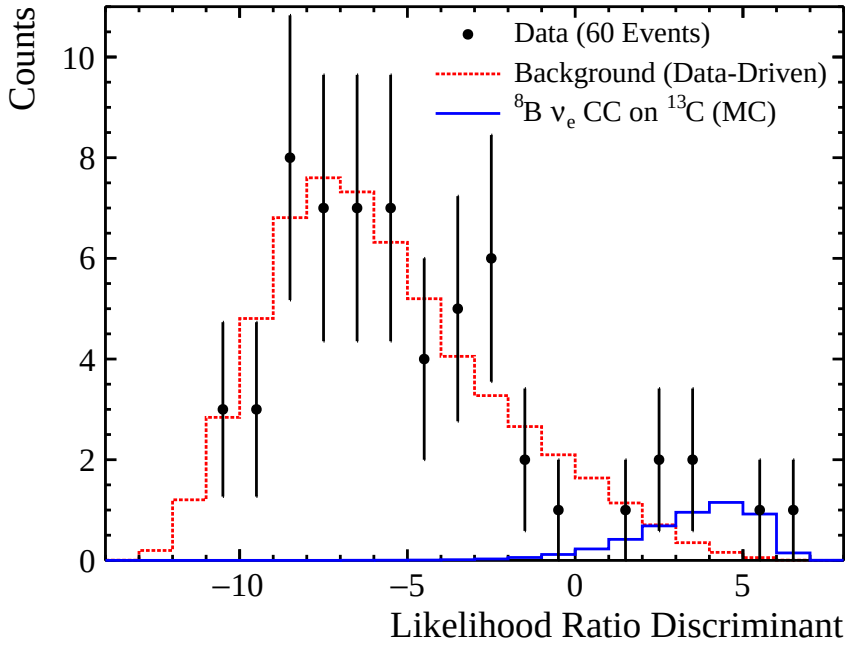
Prompt e⁻ energy = $E(\nu_e) - 2.2\ MeV$



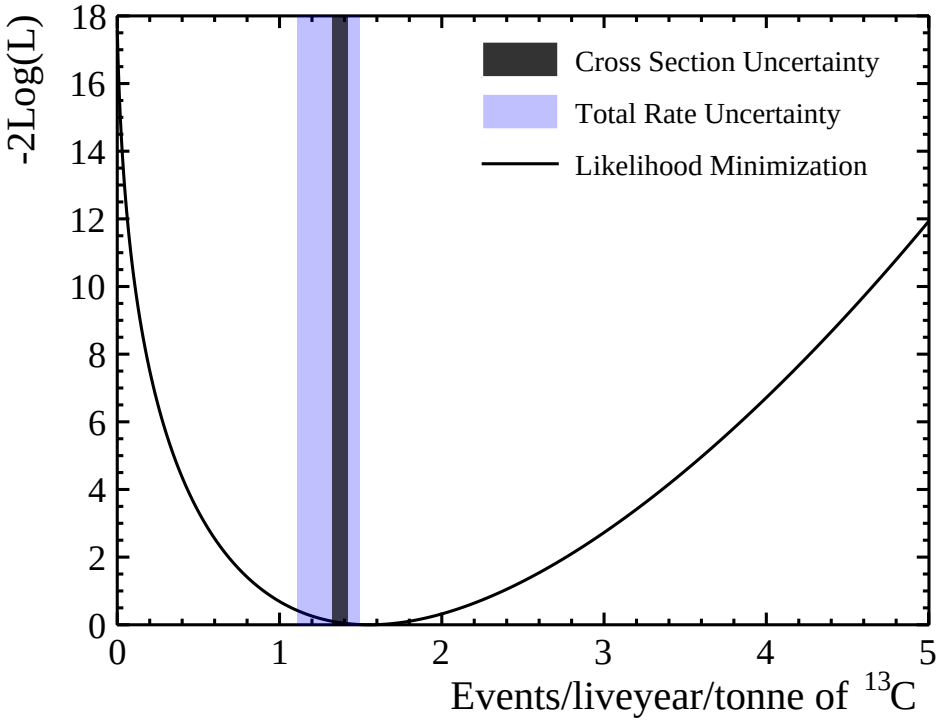
Delayed e⁺ annihilation [1.01,2.20] MeV

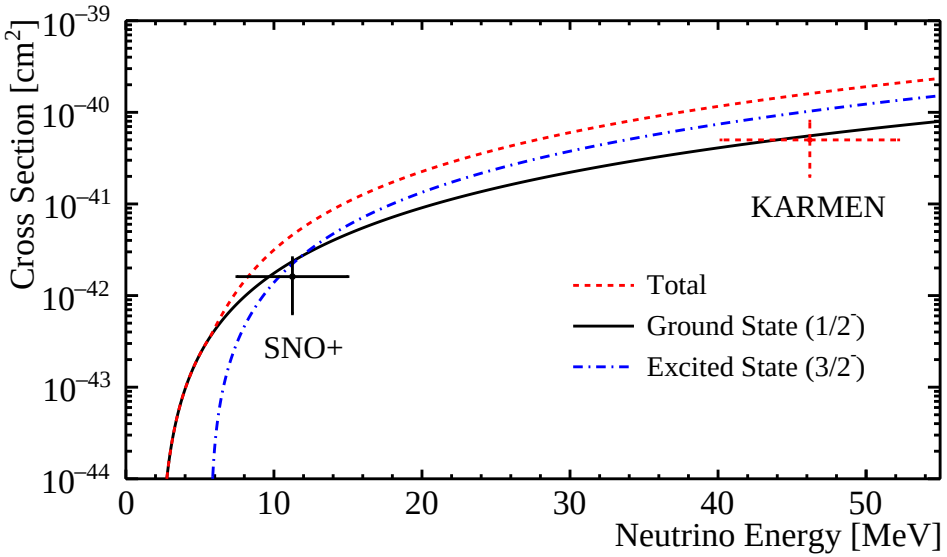
- arxiv:2508.20844
- First observation with solar neutrinos
- Likelihood approach with coincidence selection





C13 Solar Neutrino Charge Current Detection

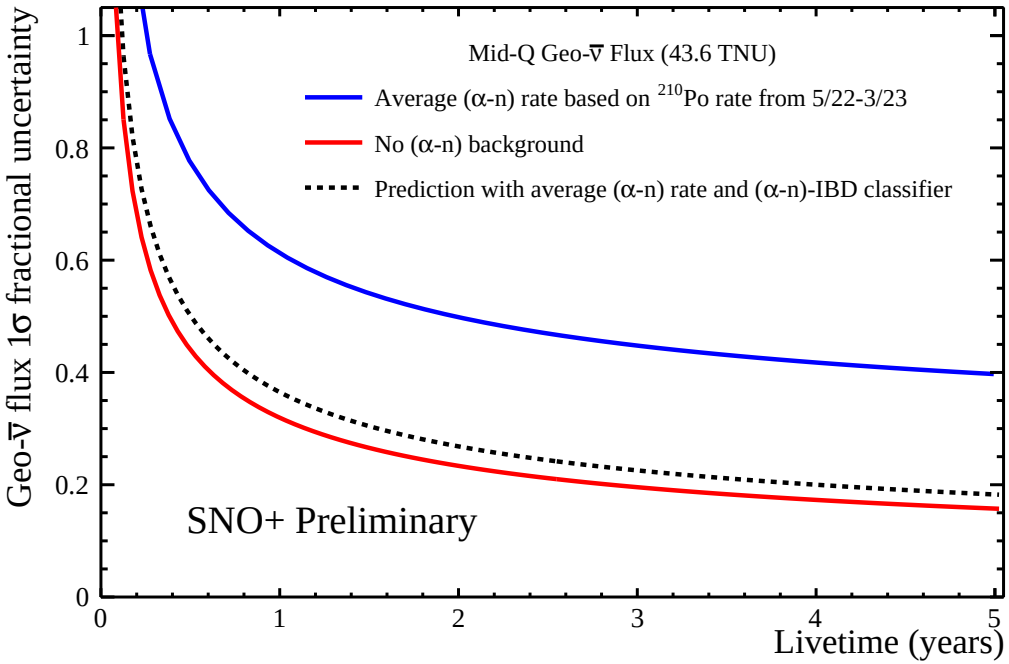




- Null hypothesis rejected at 4.2σ

- Measure rate of $1.6^{+0.82}_{-0.65}$ ev/year/tonne of ^{13}C
- Flux-weighted average cross-section:
  - $(16^{+8.5}_{-6.7}(stat)^{+1.6}_{-2.7}(sys)) \times 10^{-43}$ cm^2

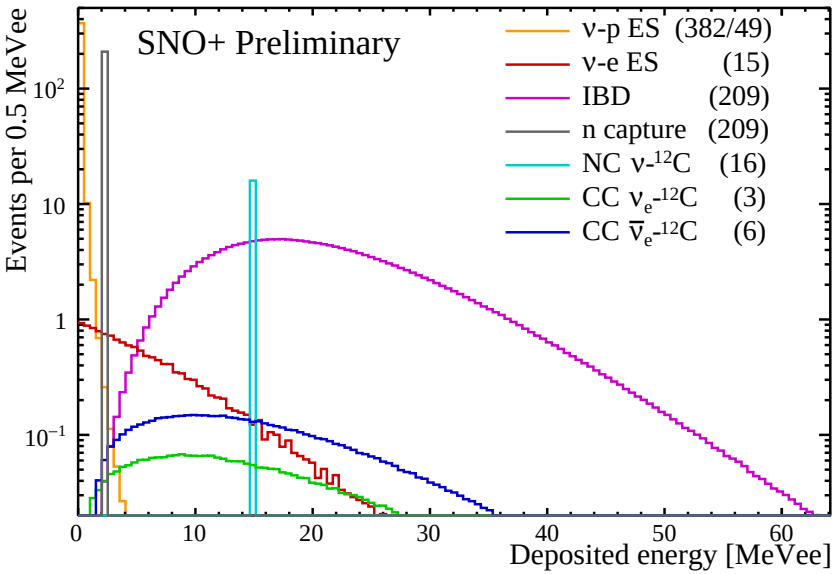
Geo-Neutrinos

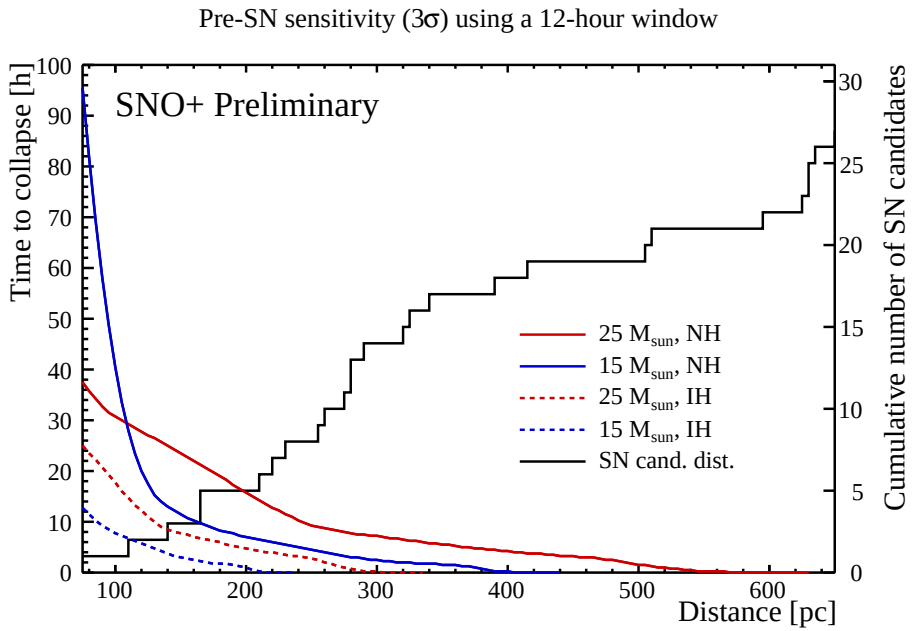


- Parallel measurement with reactor neutrinos
- Sensitivity will improve with livetime

- Measured IBD rate of 73 $^{+47}_{-43}$ TNU
- Probe the abundance of heat-producing elements; U and Th
  - Result to be combinated with KamLAND and Borexino
- Improvements in (α, n) discrimination will improve sensitivity

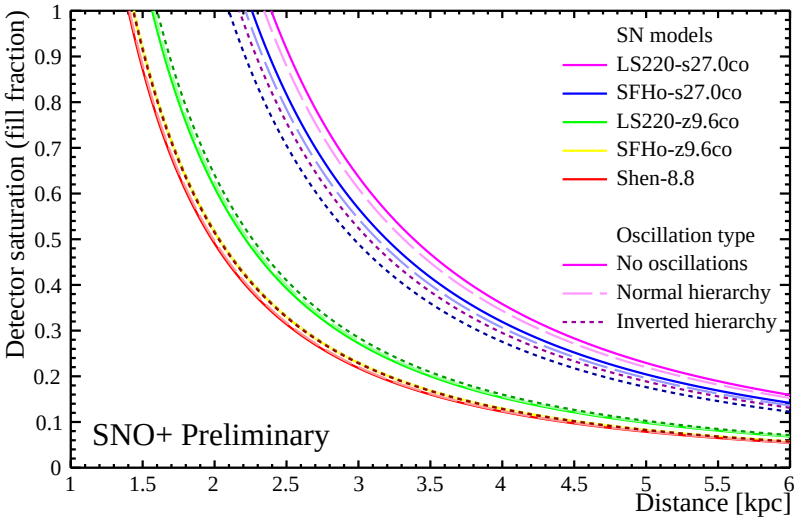
Pre-supernova neutrinos

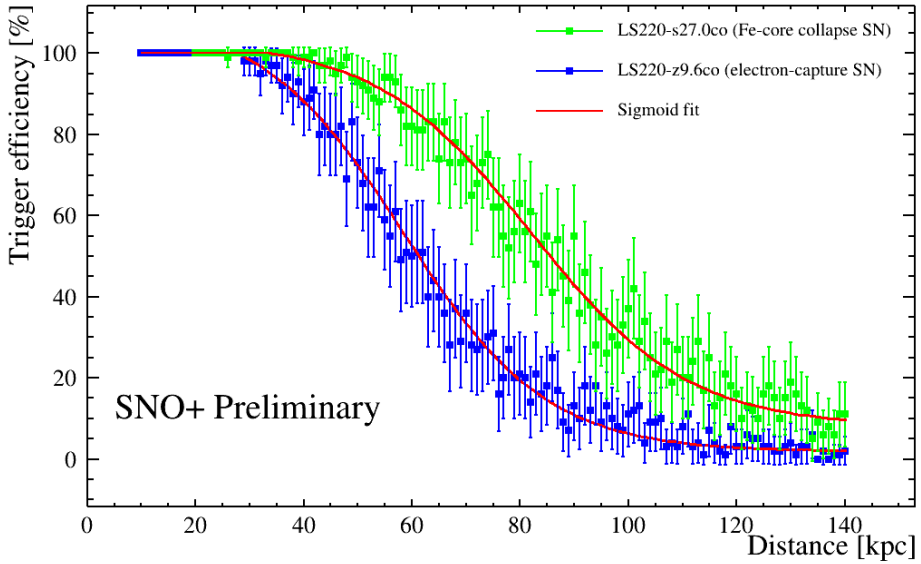




- IBDs provide early Supernova signal
  - Rate expected to increase on the days in advance of a CCSN
  - Online monitoring systems currently functional
- Evaluation made assuming Partial Fill (α, n) rates
  - Expect to improve sensitivity given reduced background

Sensitivity to Supernovae

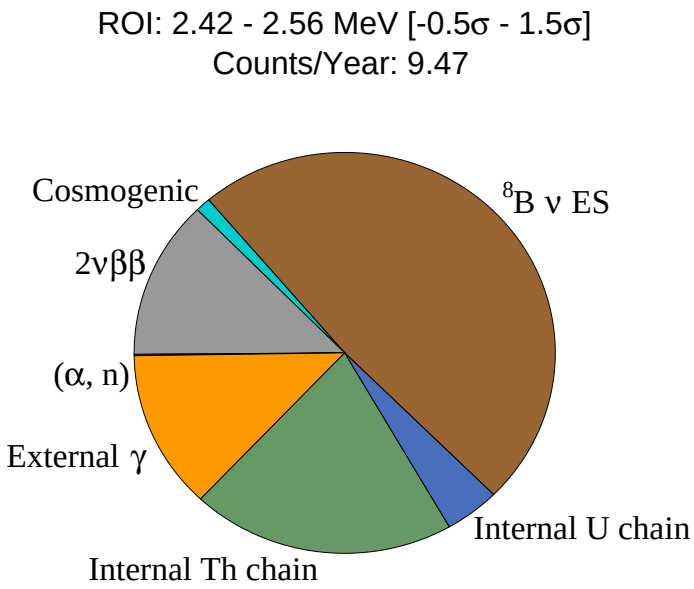


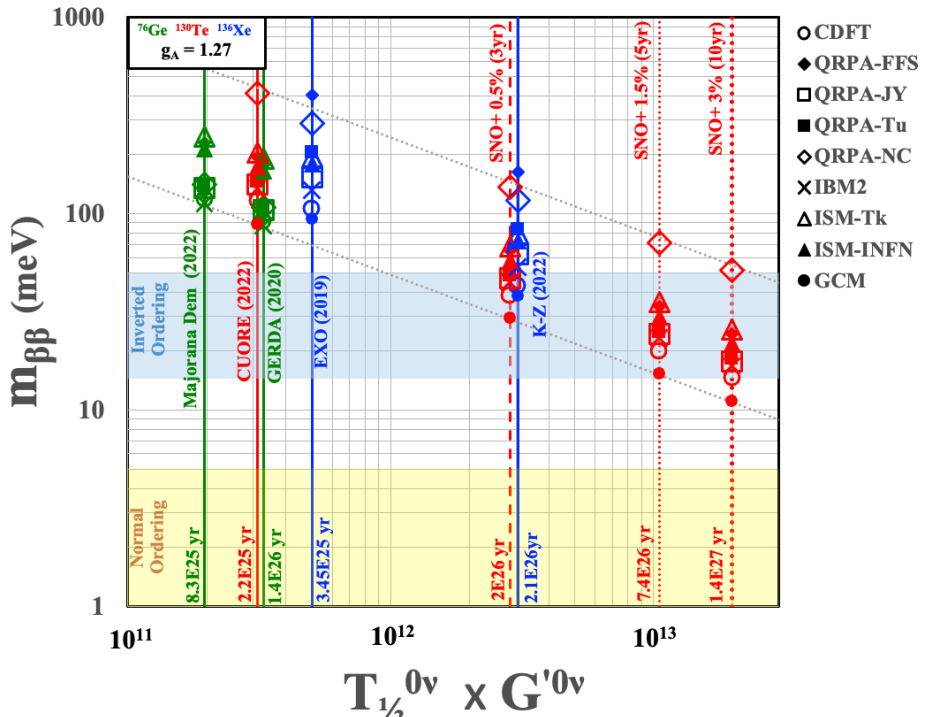


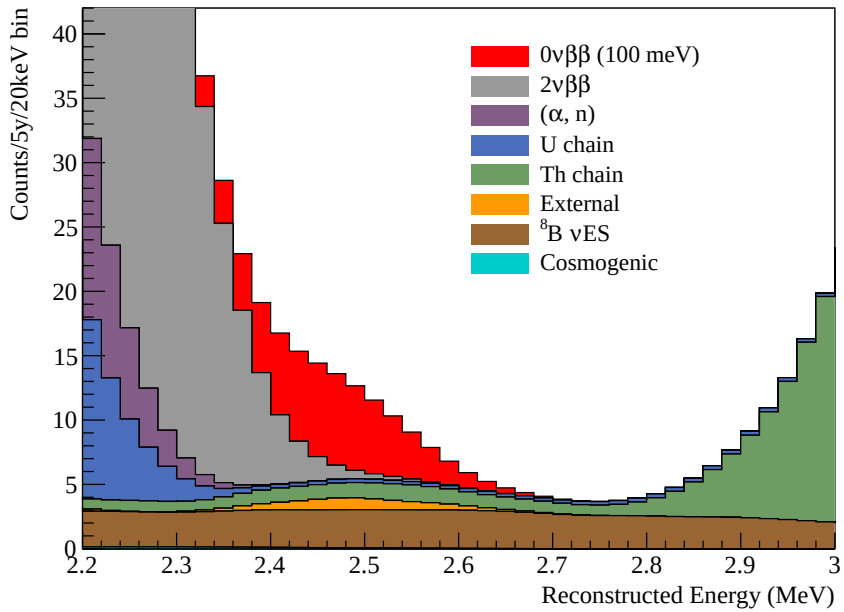
- SNO+ will saturate for close Supernova
  - Saturation limit determined by stress testing detector
  - Improved stress test in planning for coming year
- Limits are highly model dependent
- Study of IBD/ES in surrounding water could double the target mass and extend sensitivity

Neutrinoless Double Beta Decay Outlook

- Will deploy ^{130}Te in scintillator
  - Natural abundance of ^{130}Te is 34%
  - Enrichment not required
- Studies of background and light yield underway

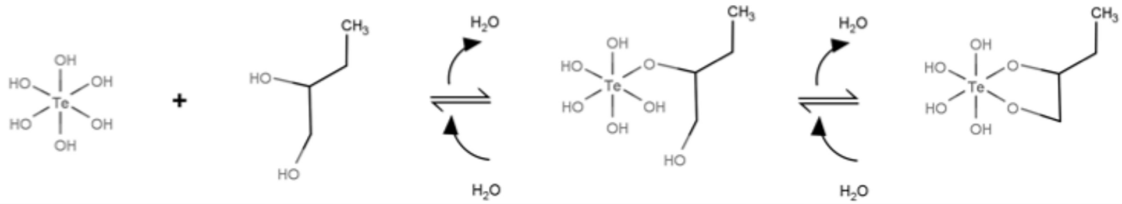






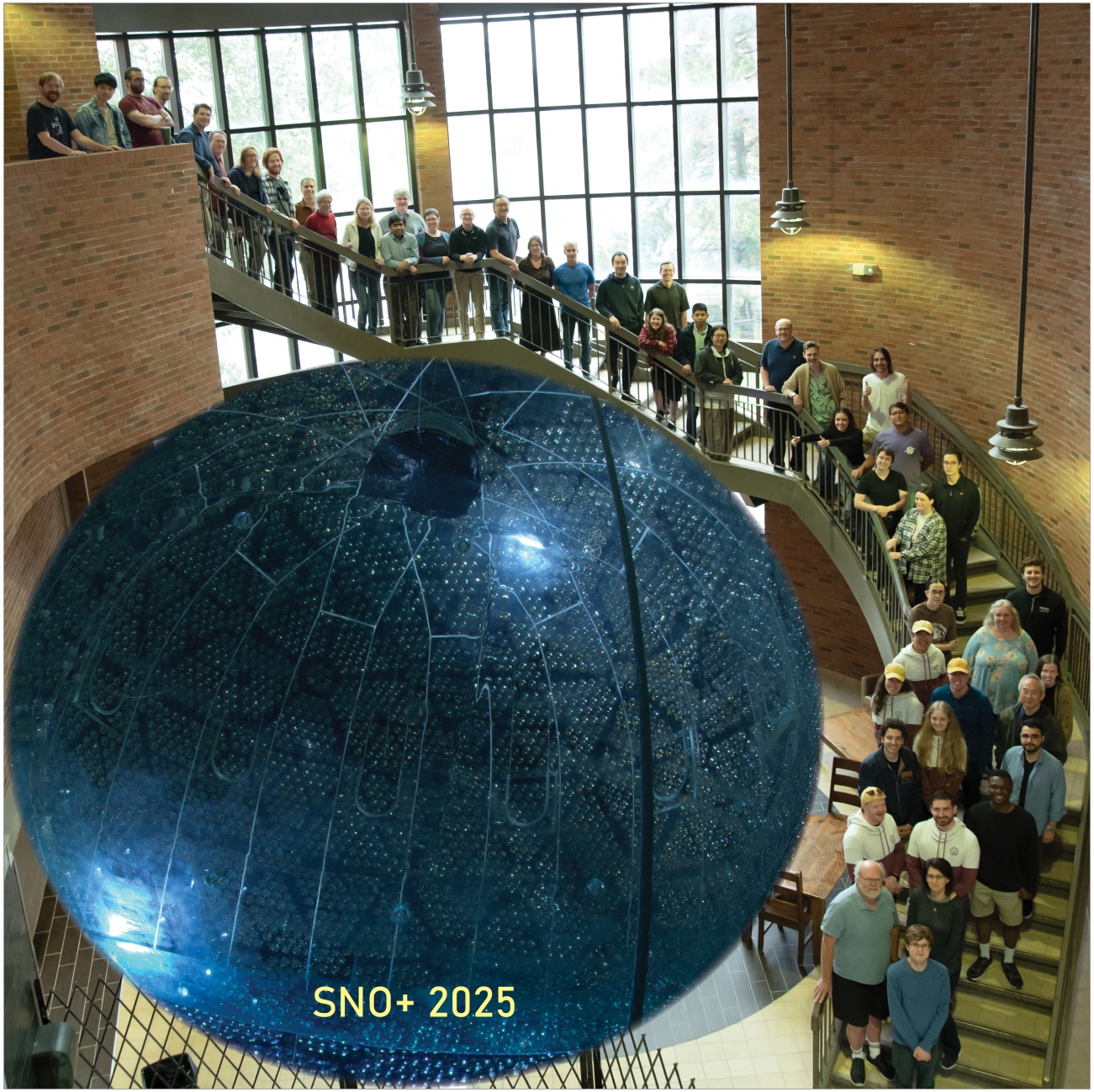
Tellurium Deployment

- Dissolved as Tellurium Butanediol
  - Synthesized from TeA and ButaneDiol
  - Stablized using DDA
  - See NIM A 795 (2015) 132-139
- Staged deployment being prepared
  - 1.3 tonnes ^{130}Te Planned
- Full-scale test batch of tellurium purification has been completed
- Further tests of purification and synthesis underway
- Planning 2026 deployment



Summary

- SNO+ has a rich physics program in process
- Results have been published for
  - Solar neutrino detection in water
  - Reactor neutrino detection in water and scintillator fill
  - Reactor $\bar{\nu}$ oscillations and observations of geoneutrinos
- New results on their way to publication
  - Solar neutrinos in scintillator
  - First detection of Solar neutrino interactions with Carbon-13
- Efforts for monitoring Supernova under way
- Progressing toward deployment of ^{130}Te for $0\nu\beta\beta$



Thank you

Backup Slides

$\bar{\nu}$ Oscillations

- General representation of neutrino oscillations

$$\bar{\nu}_\alpha = \sum_{i=1}^{3} V_{i\alpha} \bar{\nu}_i$$

- $\alpha \in \{e, \mu, \tau\}$
- Probability of electron survival in the limit pertinent to SNO+

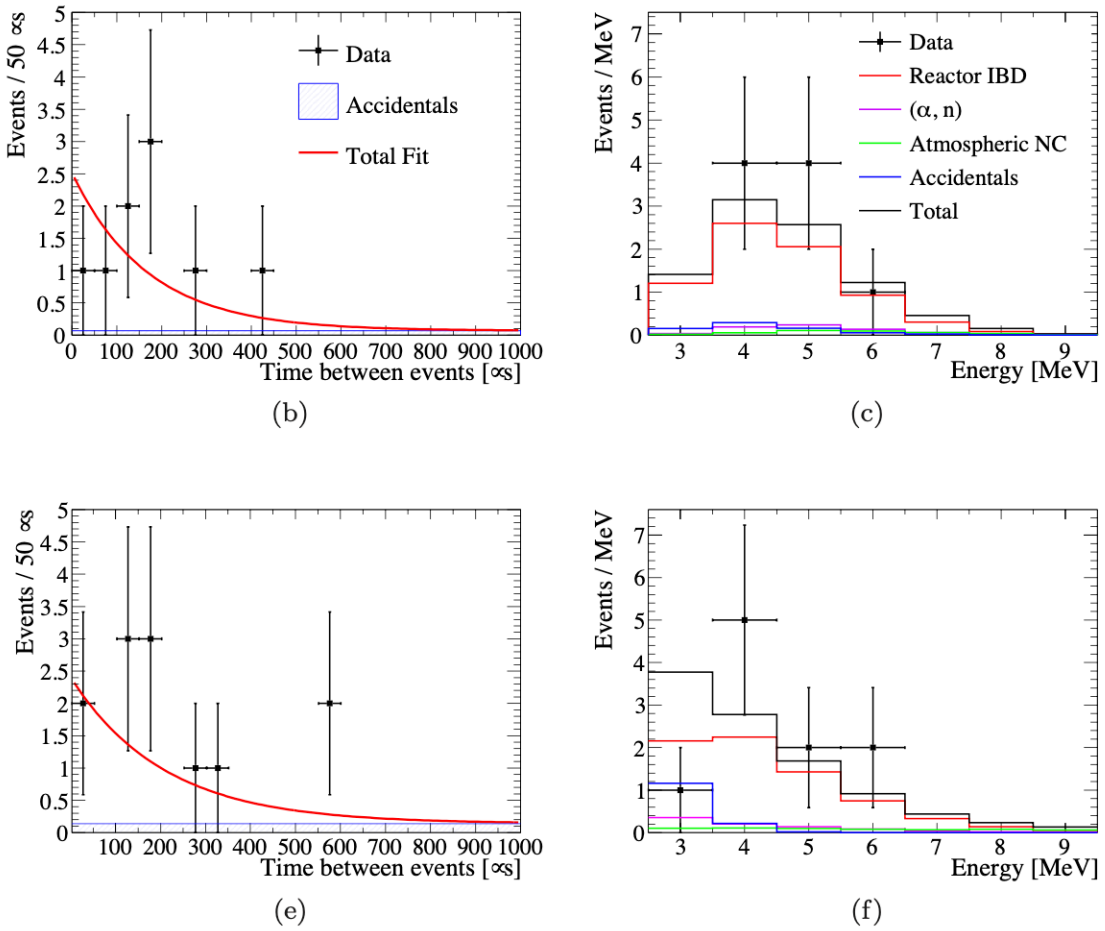
$$P_{ee} \approx (1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}) \cos^4 \theta_{13} + \sin^4 \theta_{13}$$

- $\Delta_{21} = 1.267 \Delta m^2_{12} L/E$ where E [MeV] is the $\bar{\nu}$ energy and L [m] is the distance travelled
- $\Delta m^2_{12} = m^2_1 - m^2_2$ [eV^2]
- Current averages:
  - $\sin^2 \theta_{12} = 0.307 \pm 0.013$
  - $\Delta m^2_{12} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2 (KAMLAND + global solar)
  - **But:** SK+SNO global solar $\Delta m^2_{12} = (4.8^{1.3}_{-0.6}) \times 10^{-5}$ eV^2
- SNO+ can measure both solar and reactor neutrino spectra
  - Resolve the existing tension

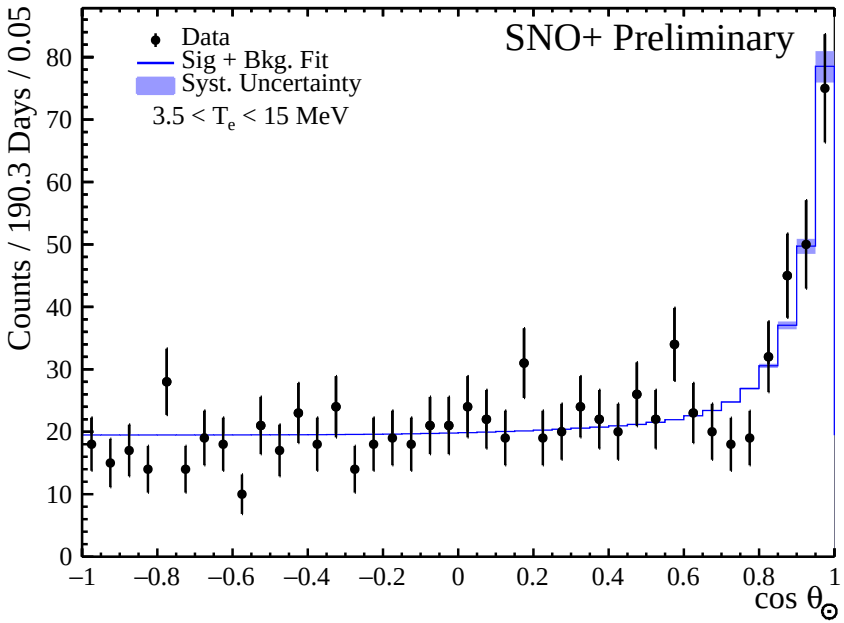
First observations of reactor neutrinos in water

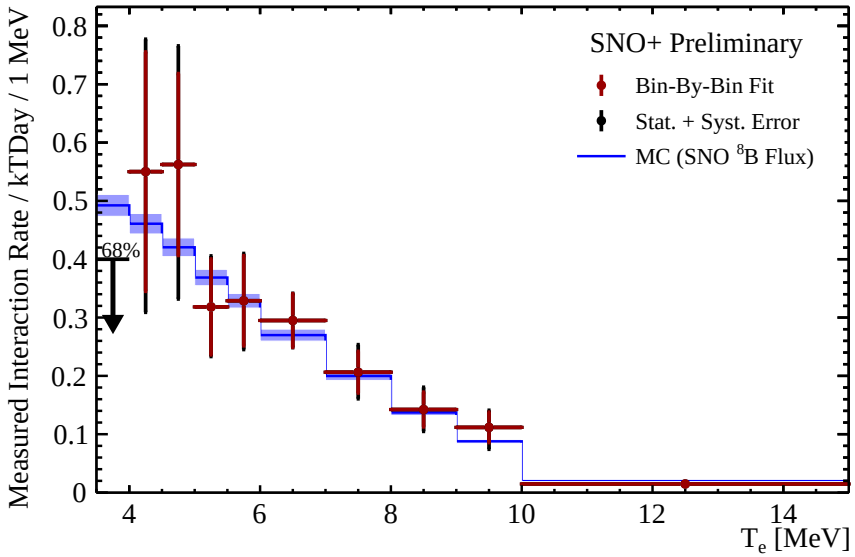
PhysRevLett.130.091801

- Parallel analyses conducted
  - Likelihood Ratio
  - Boosted Decision Tree
- Demonstrated 3.5σ evidence of rector $\bar{\nu}$ events in water



Final SNO+ Solar Neutrino Measurements in Water





- Phys.Rev.D 110 (2024) 12, 122003
- Measure ^8B solar neutrino flux from 282.4 live days
  - $2.32^{+0.18}_{-0.17}(stat.)^{+0.07}_{-0.05}(syst.) \times 10^6 cm^{-2}s^{-1}$ assuming no ν oscillations
  - $5.36^{0.41}_{0.39}(stat.)^{0.17}_{-0.16}(syst.)) \times 10^6 cm^{-2}s^{-1}$ assuming standard ν oscillations