# Anti-Neutrinos in SNO+:

## Results and Future Prospects

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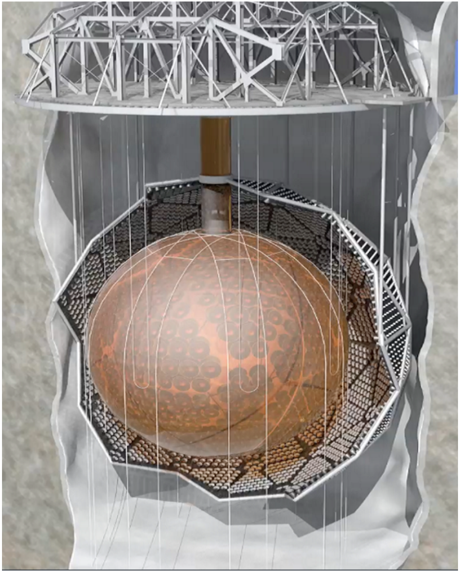
SNOLAB User's Meeting
June 27

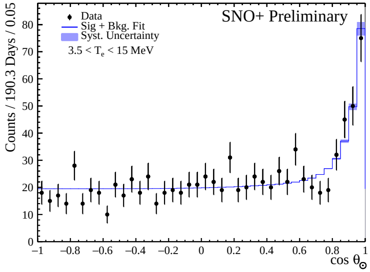
# Introduction to SNO+

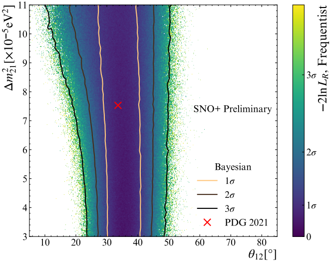
- SNO+ is a multipurpose neutrino detector
  - Primary mission to search for $0\nu\beta\beta$
  - Additional measurements of Solar, **Reactor**, **Geo**, **Supernova** neutrinos accessible
- Detection of neutrons allows for the detection of anti-neutrinos via Inverse Beta Decay (IBD)

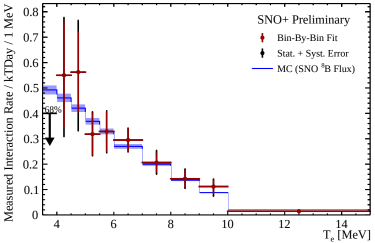


# New Results from SNO+ Presented at Neutrino 2024

- Final water solar
- Full Fill LS solar
- First indications of Charge Current $^{8}B$ neutrino capture on $^{13}C$
- Partial fill $\bar{\nu}$
- Full fill $\bar{\nu}$



# $\bar{\nu}$ Oscillations

- General representation of neutrino oscillations

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

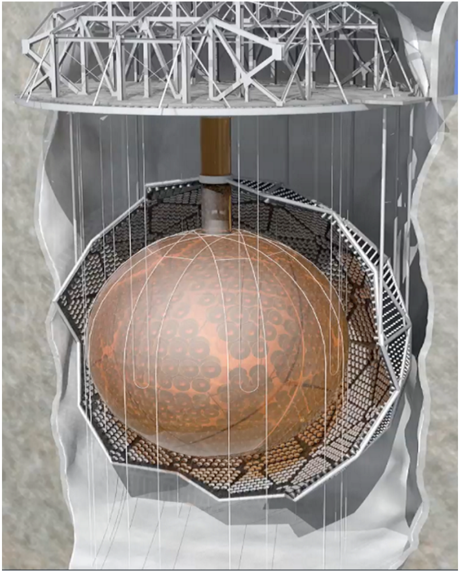
- $\alpha \in \{e, \mu, \tau\}$
- Probability of electron survival in the limit pertinent to SNO+

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

- $\Delta_{21} = 1.267\Delta m^2_{12} L/E$ 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

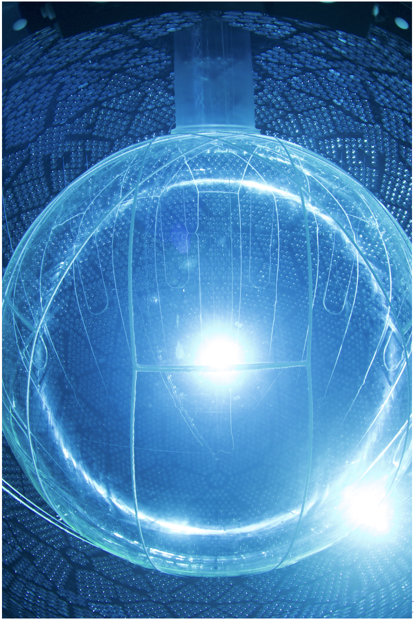
# The SNO+ Detector

- 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

- 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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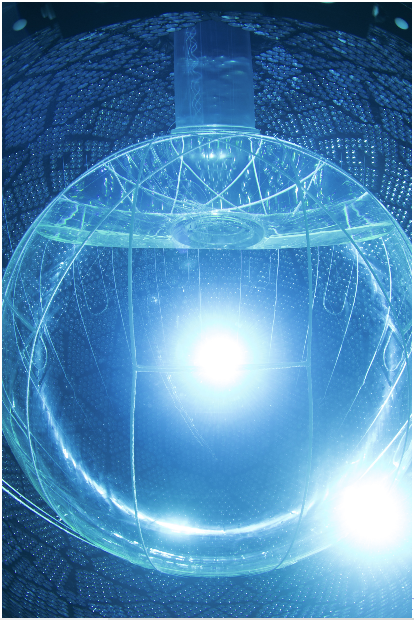

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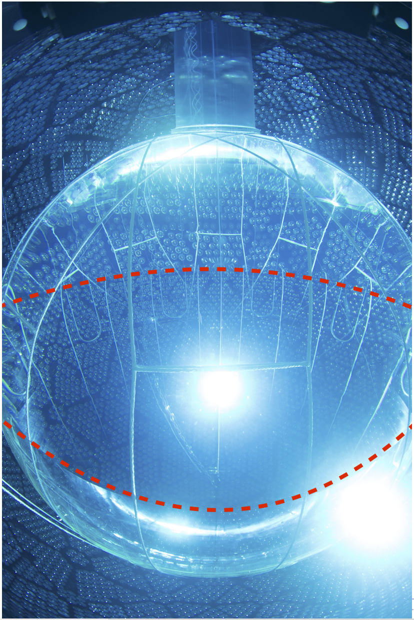

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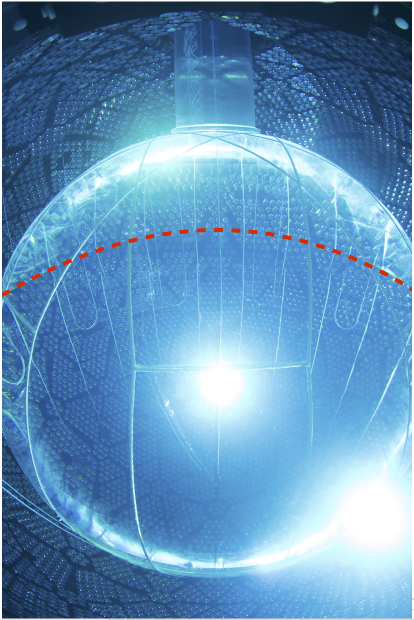

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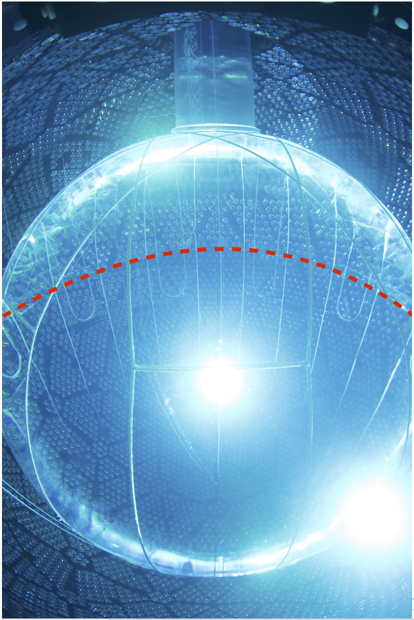

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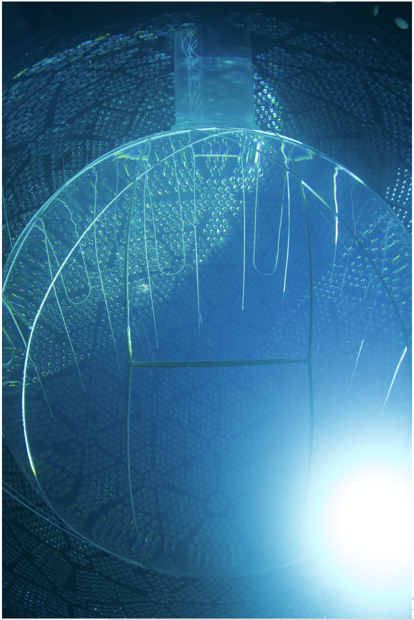
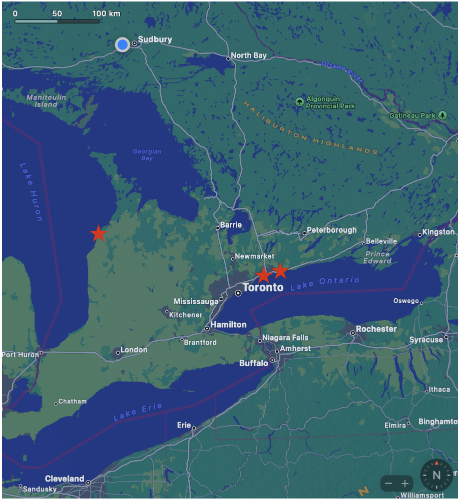


# $\bar{\nu}$ at SNO+

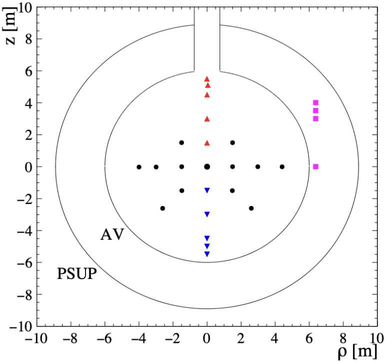
- $\bar{\nu}$ can be observed from
  - Reactors
    - Bruce (240 km)
    - Pickering (340 km)
    - Darlington (350 km)
    - Various US reactors
  - Earth (Geo-$\nu$)
  - Core Collapse Supernova
- $\bar{\nu} p \rightarrow e^+ n$
  - Threshold of 1.806 MeV
  - n-H capture produces 2.2 MeV $\gamma$
  - Positron boosts visible energy by 1 MeV

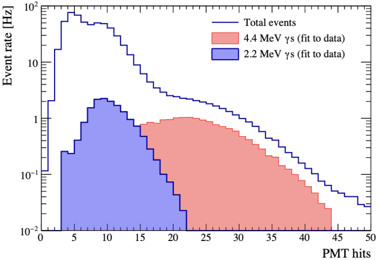


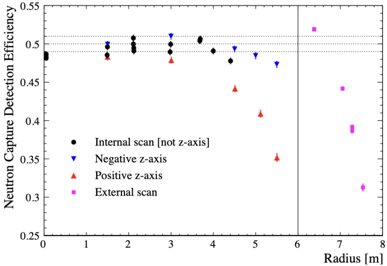
# Validating IBD in Water

https://doi.org/10.1103/PhysRevC.102.014002

- Deployed neutron (AmBe) source in water
- Demonstrated 50% detection efficiency



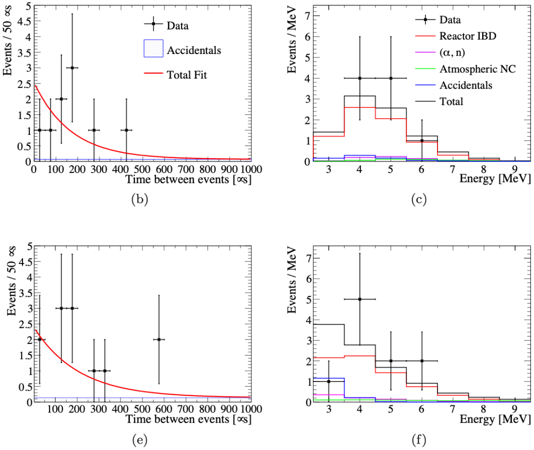



# First observations of reactor neutrinos in water

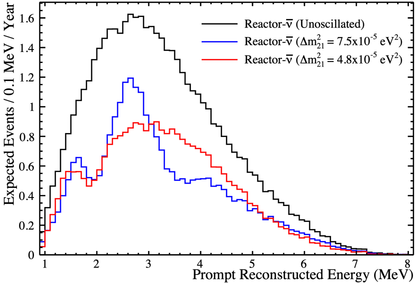
https://doi.org/10.1103/PhysRevLett.130.091801

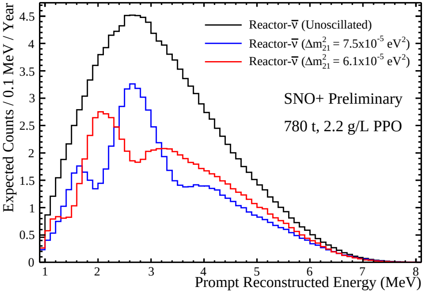
- Parallel analyses conducted
  - Likelihood Ratio
  - Boosted Decision Tree
- Demonstrated 3.5$\sigma$ evidence of rector $\bar{\nu}$ events in water



# Reactor Neutrino Prediction at SNOLAB

- $2 \times 10^{20}$ $\bar{\nu}$ per second per GW of thermal power
- Rate from CANDU reactors estimated from hourly IESO data
- Rate from other reactors estimated from monthly averages from IAEA

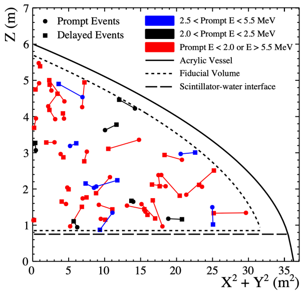


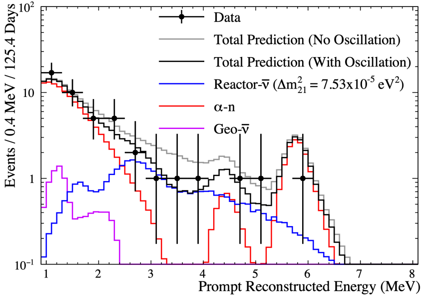




- Changes in $\Delta m^2_{12}$ expected to be significant

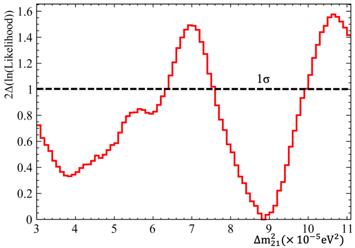
# Partial Scintillator Fill Data and Results

arXiv:2405.19700

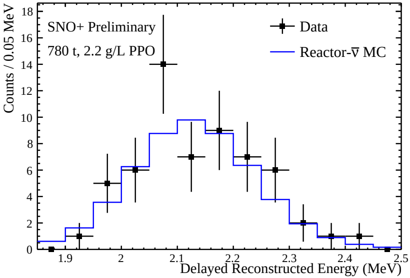


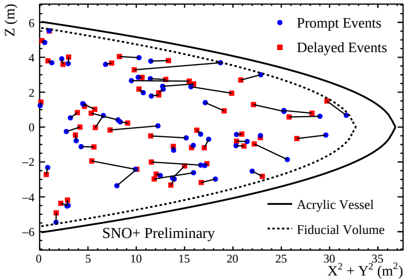




- 114 tonne-years of data
- Log likelihood fit of prompt spectra
  - Individual oscillations for ON reactors
  - Average of reactors at > 1000 km
  - A single spectrum for Geoneutrinos
- $\theta_{12}$ fixed to global average
- Best fit: $\Delta m^2_{12} = (8.85^{+1.10}_{-1.33}) \times 10^{-5}$ eV$^2$



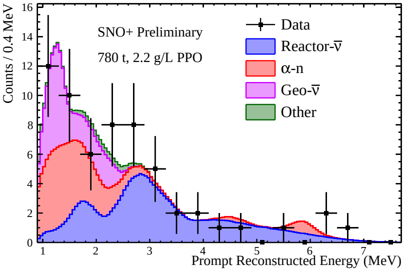
# Preliminary Reactor $\bar{\nu}$ in Full Scintillator Detector

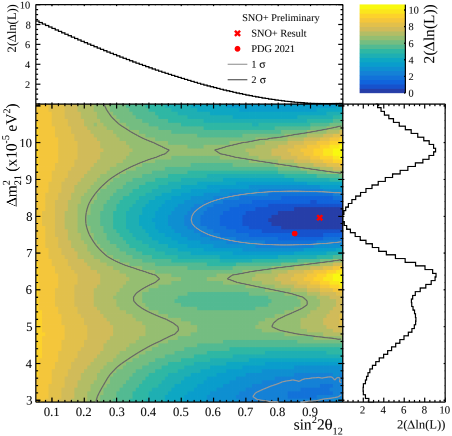



- Used data collected between April 2022 - March 2023
  - Stable running period following PPO addition
- Reduced $(\alpha, n)$ specific activity
  - $^{210}$Po decays with 138 day half-life
- Improved light yield improves position and energy resolution

# Oscillation Measurements




- Improvements in background rejection and statistics clear in stacked plot

- Allows $\Delta m^2_{12}, \sin^2 2\theta_{12}$ fit
- Best fit at $\Delta m^2_{12} = (7.95^{+0.48}_{-0.41}) \times 10^{-5}$ eV$^2$
- Can approach global average uncertainty in 3 years exposure

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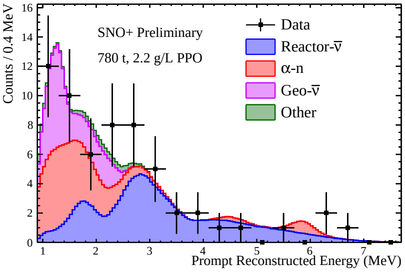


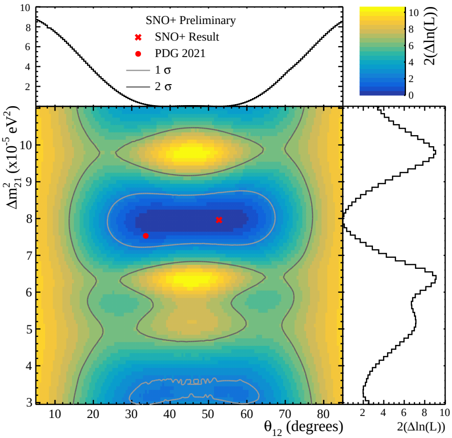


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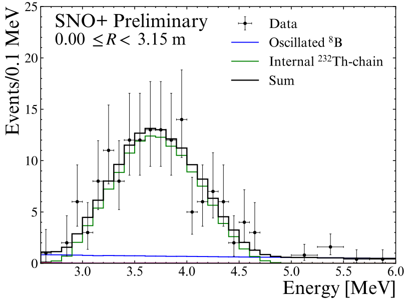
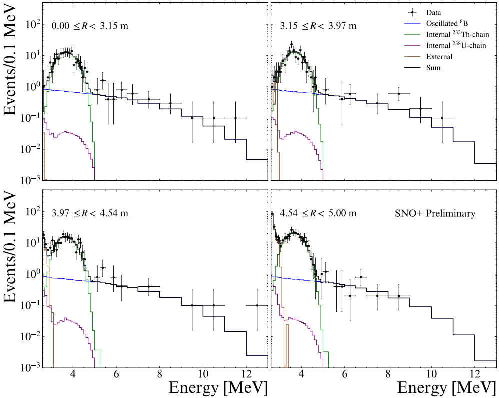
# Solar Neutrino Detection

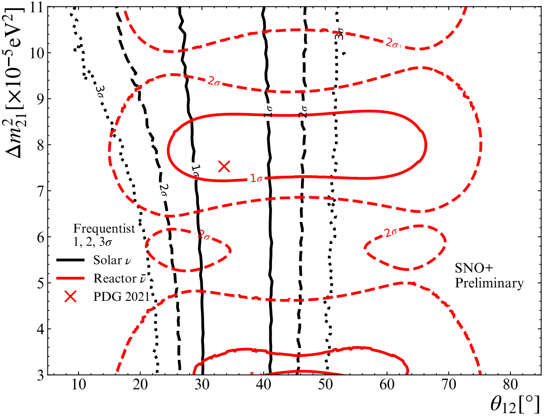
- Measurement of solar neutrinos in progress
- Elastic electron-neutrino scattering signal




- Complementary oscillation measurement
  - More sensitive to $\theta_{12}$

# Combination with Solar neutrino results




- Adding solar data better constrains $\theta_{12}$ in addition to $\Delta m^2_{12}$
- Resolves tension in measurements to be consistent with KAMLAND

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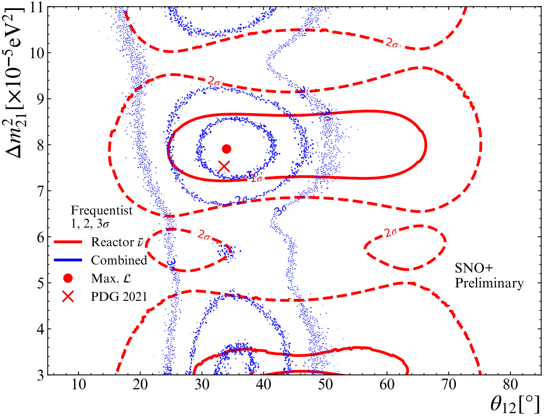


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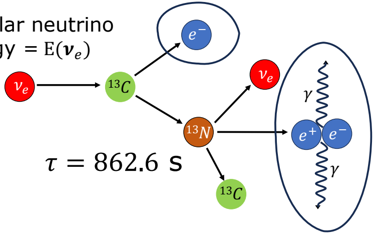
- Resolves tension in measurements to be consistent with KAMLAND

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

Prompt e⁻ energy = $E(\boldsymbol{\nu}_e) - 2.2\ MeV$

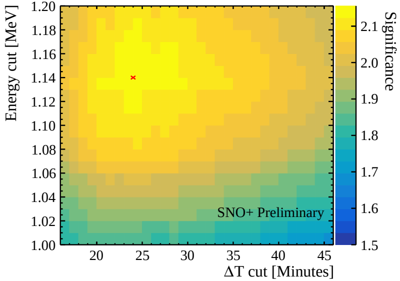
$^{8}B$ solar neutrino energy = $E(\boldsymbol{\nu}_e)$

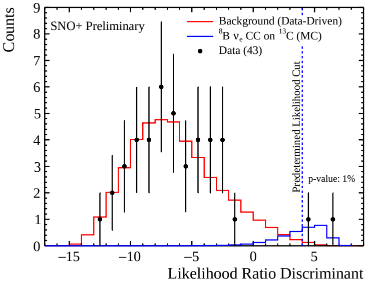



$\tau = 862.6$ s

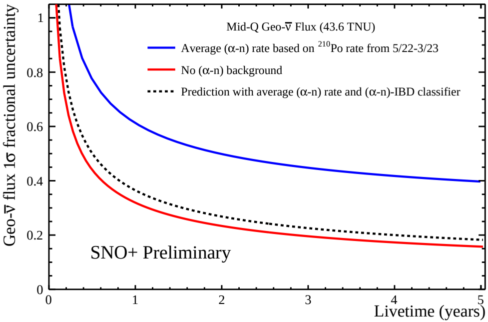
Delayed e⁺ annihilation [1.01,2.20] MeV

- Similar to IBD, look for a prompt-delay pair of event
- Much longer $\Delta t$



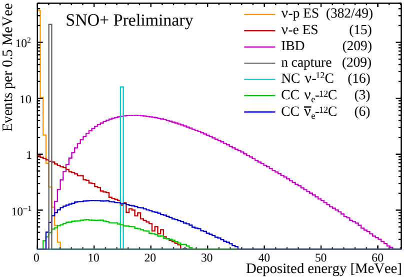
# Geo-neutrinos

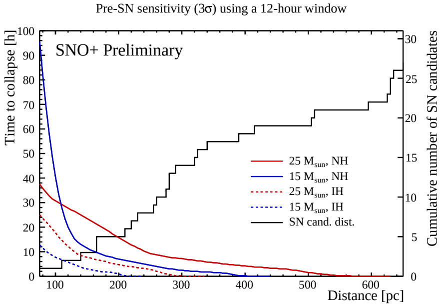



- Parallel measurement with reactor neutrinos
- Sensitivity will improve with livetime

- Preliminary measured flux of $64 \pm 44$ TNU
- Potential to distinguish between different geological models
- Improvements in $(\alpha, n)$ discrimination will improve sensitivity
- Dedicated measurement forthcoming

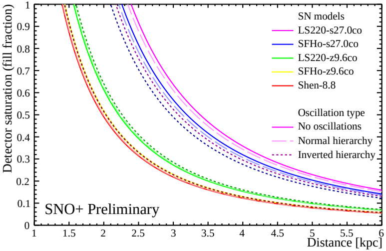
# Pre-supernova neutrinos

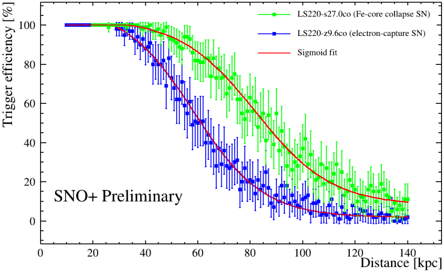



- IBDs provide early Supernova signal
  - Rate expected to increase on the days in advance of a CCSN
  - Online monitoring systems currently functional
- Evaluation made assuming Partial Fill $(\alpha, n)$ rates
  - Expect to improve sensitivity given reduced background
  - Yet to add $(\alpha, n)$ classifier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

# 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 in surrounding water could double the target mass and extend sensitivity

# Conclusion

- $\bar{\nu}$ produces a neutron tagged signal from IBD in SNO+
  - Shown to be observable in water with 50% efficiency
- Multiple results in reactor neutrinos and more to come.
  - First Evidence by a pure water Cherenkov detector
  - Observation oscillations in partial scintillator
  - Measurement of oscillations in full scintillator (in progress)
  - Geo-neutrino flux from same fit at 64 $\pm$44 TNU
  - Combination with solar neutrino measurements in SNO+
- Will contribute to Supernova early warning systems
  - $\bar{\nu}$ signal to arrive long before optical signal
  - Seeking membership in SNEWS2
- New and exciting measurements from SNO+ in progress
  - Solar neutrinos papers in water and scintillator forthcoming
  - CC Interactions between $^{13}$C and $^{8}$B Solar Neutrinos