

Antineutrinos in SNO+

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for the SNO+ collaboration

WIN 2025, Sussex University, June 2025

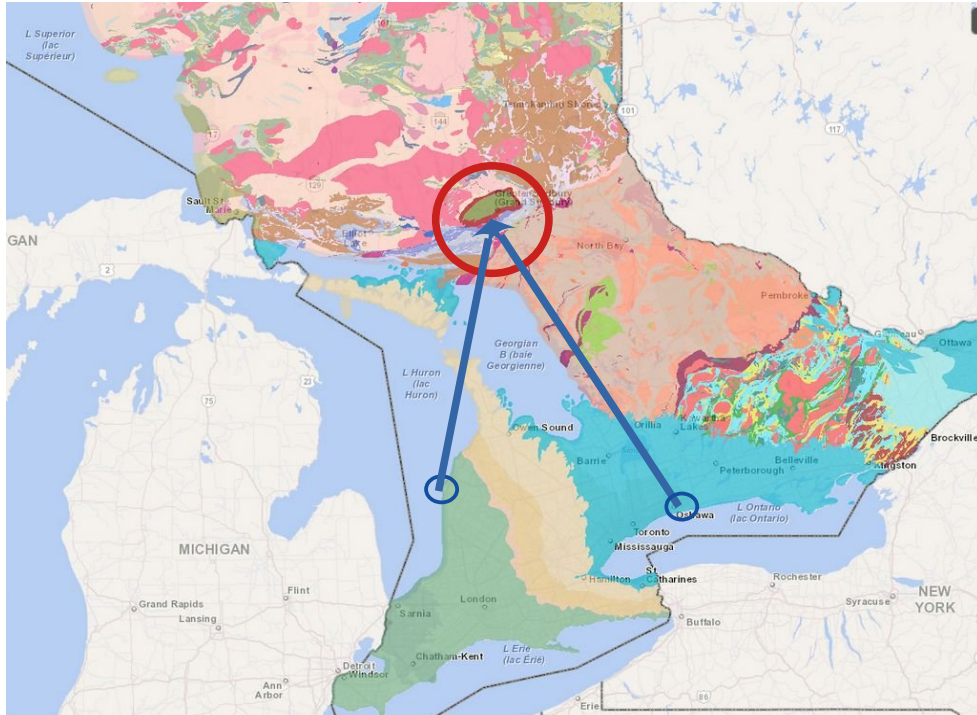


LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS



antineutrinos at SNOLAB, Canada

SNO+ is 2 km deep



Around half of the antineutrinos from nuclear power plants at **240 km** and **350-355 km**

More antineutrinos from reactors at varying distances and from North American **geoneutrinos**

antineutrinos in all SNO+ phases

SNO+ now contains 780 tons of liquid scintillator
with high radio-purity (4×10^{-17} g/g ^{238}U , 5×10^{-17} g/g ^{232}Th)
with 4% energy (and 12 cm) resolution at 2.5 MeV

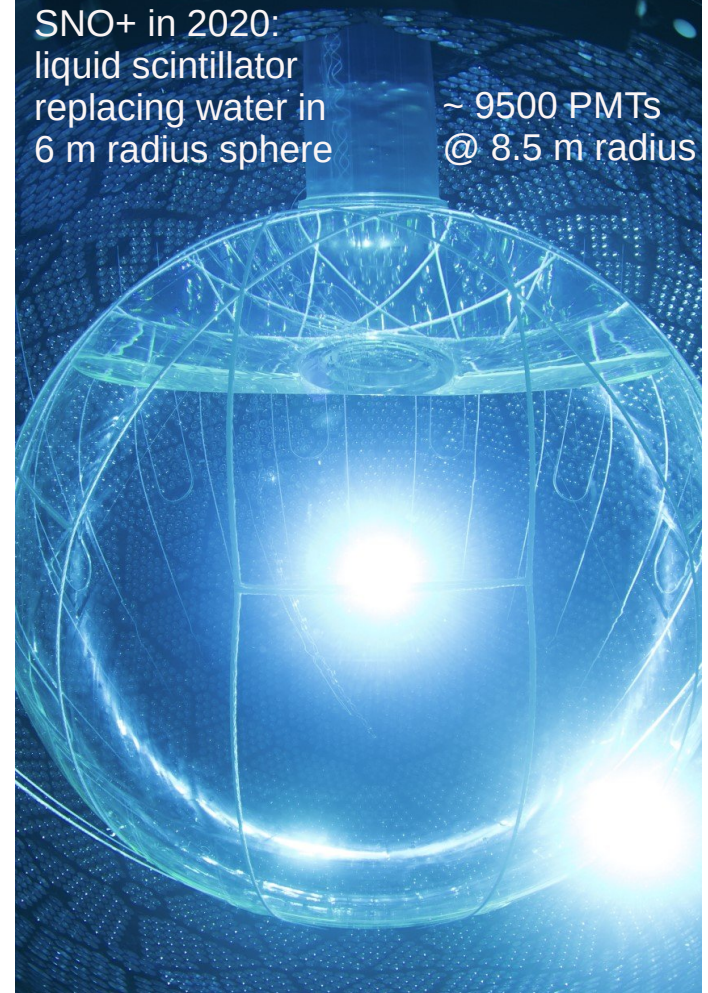
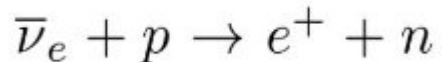
Evidence of antineutrinos from distant reactors using pure water,
PRL 130, 09180 (2023) with low threshold, high purity water data

Initial measurement of reactor antineutrino oscillation,
EPJC 85, 17 (2024) with partial fill (LAB in upper half) data

Measurement of reactor antineutrino oscillation,
submitted (2025), arXiv:2505.04469, with the first full-fill data

Data collected as scintillator cocktail changed
LAB + (0.6 to 2.2 g/L) PPO + 5.5. mg/L BHT + 2.2 mg/L bis-MSB

IBD detection possible also with Tellurium loaded for $0\nu\beta\beta$ search



reactor (and geo) signals

60% ν flux Canadian PHWR reactors
(constant refueling / hourly power info)

40% ν flux American P/BWR reactors,
(average over 100s / monthly power info)

	^{235}U	^{239}Pu	^{238}U	^{241}Pu
PHWR	0.52	0.42	0.05	0.01
P/BWR	0.57	0.30	0.08	0.06

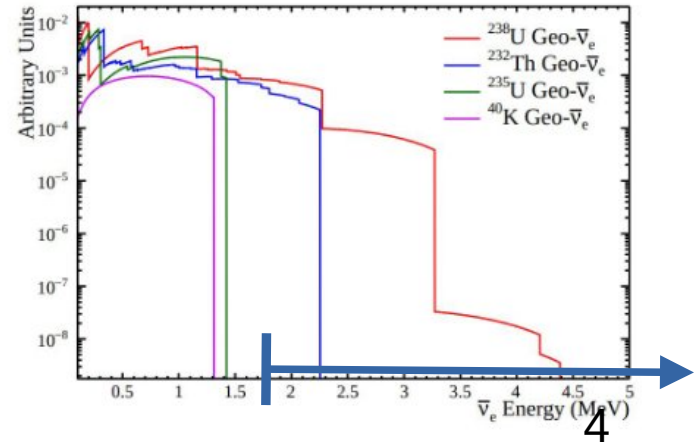
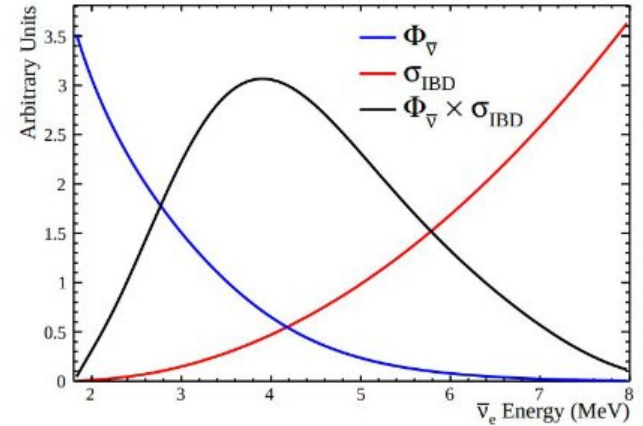
Reactor spectra scaled to global average reactor measurement
Systematic uncertainties cross-checked with detailed Daya Bay studies

$$\begin{aligned}
 P_{ee} &= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\
 &\quad - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) \\
 &\approx (1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}) \cos^4 \theta_{13} + \sin^4 \theta_{13},
 \end{aligned}$$

* using full three neutrino mixing framework which includes matter effects over constant electron density of North American crust ($8.13 \times 10^{23} \text{ cm}^{-3}$)

For geoneutrinos, our model uses 20 TW, $\langle P_{ee} \rangle = 0.55$,
to predict 36.3 ± 8.7 TNU from ^{238}U and 9.7 ± 2.3 TNU from ^{232}Th
but we assume 100% uncertainty in total rate with U/Th $\sim 3.7 \pm 1.3$

(1 TNU = 1 IBD event per year per 10^{32} protons)

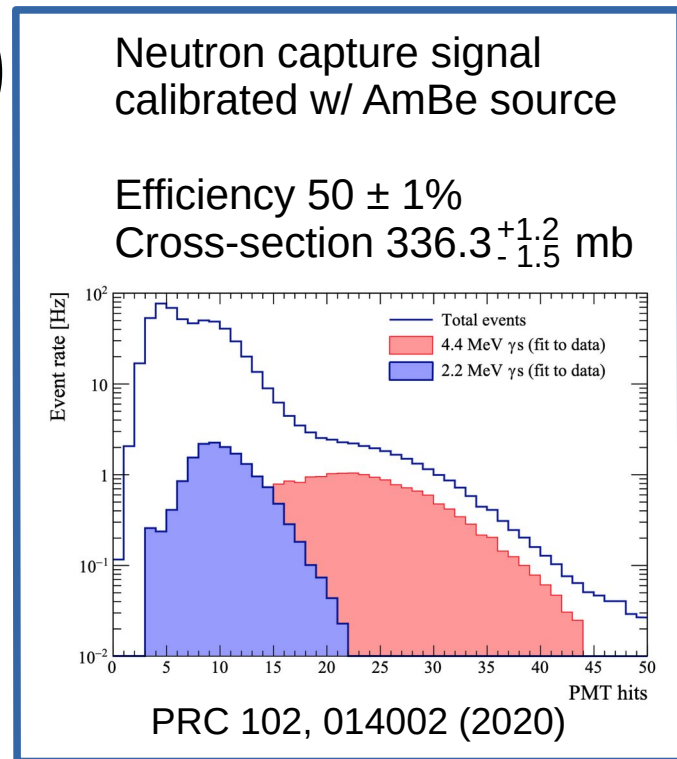
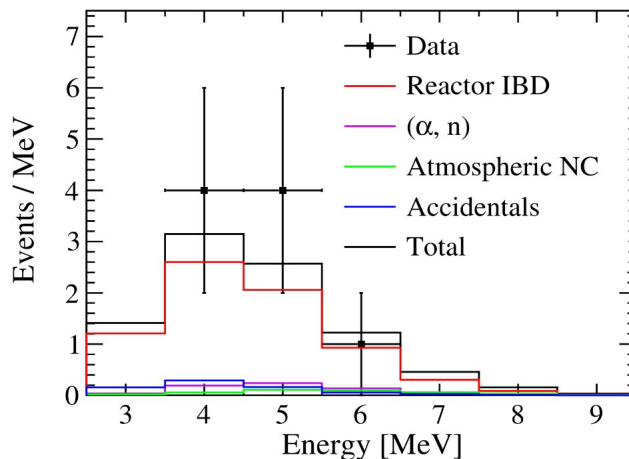
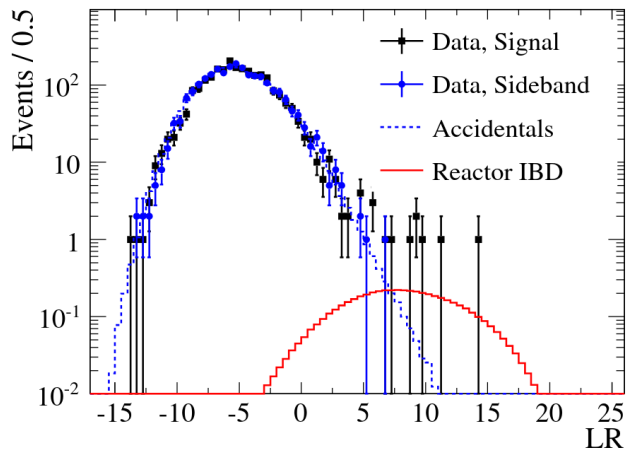


antineutrino in water (& accidental backgrounds)

190 days (2017-2019), 2 indep. analyses, 3.5 sigma evidence

Accidental model built from data; sideband for ΔT in [0.5,1] ms

LR efficiency 45% for a background reduction of 10^{-4}

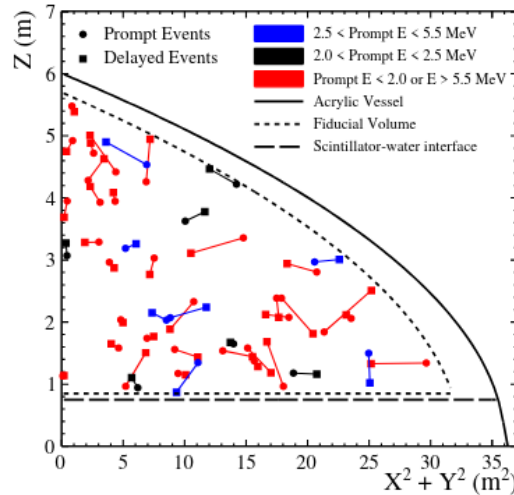
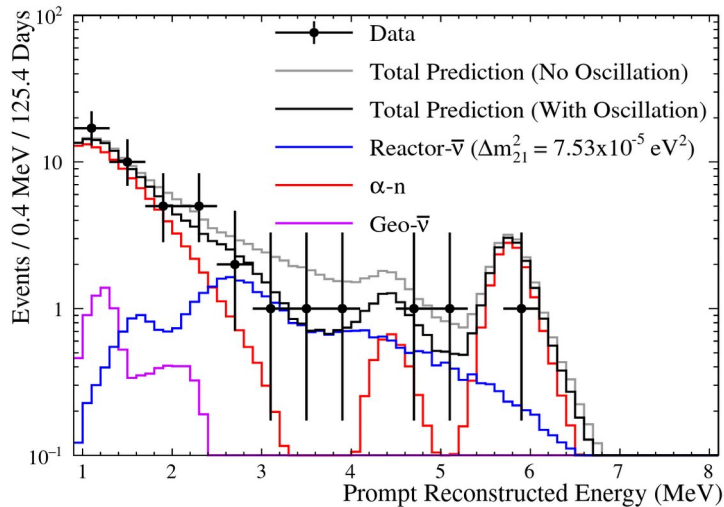


← PRL 130, 09180 (2023)

partial fill analysis & (α, n) background

(α, n) dominant source is ^{210}Po α , directly measured from data
specific activity strongly reduced from partial to full fill phase...

$\alpha + ^{13}\text{C} \rightarrow ^{16}\text{O}^* + n$ (low E) with O^* de-excitation
 $\rightarrow ^{16}\text{O} + n$ (high E) with scatter on p and C



Scintillator time profile, yield,
quenching, and reconstruction
calibrated with β - α backgrounds

from $^{214}\text{Bi}/^{214}\text{Po}$ decays fed by
radon ingress into scintillator
during detector operations

	Prediction	Fit result
Reactor IBD	9.5 ± 0.3	9.5 ± 0.3
Geo IBD	2.2 ± 2.2	2.5 ± 2.1
(α, n)	33.3 ± 12.7	32.4 ± 5.6
Sum	45.0 ± 12.9	44.4 ± 6.0
Observed		45

114 tonne-years of data (in 2020)
Low sensitivity to oscillation parameters
compatible with KamLAND and with solar

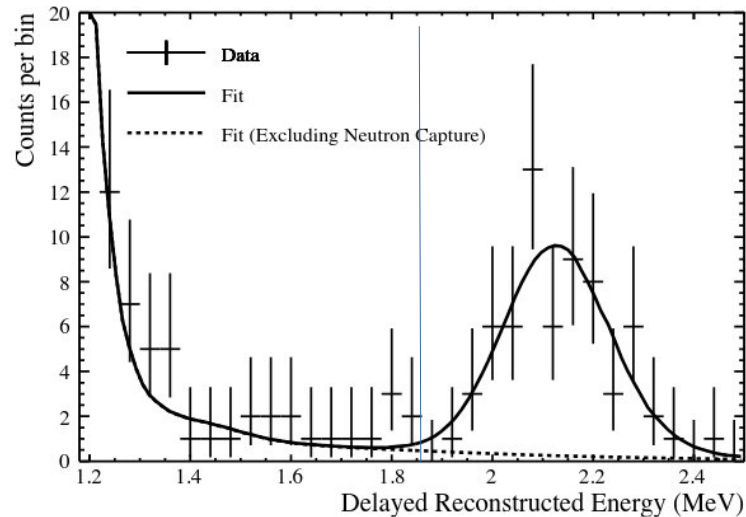
EPJC 85, 17 (2025)

first full-fill analysis & a new background

^{214}Bi ($Q=3.3$ MeV β) +
 ^{214}Po (7.8 MeV α) +
alpha-proton scatter

Smaller quenching factor for
Protons than alphas may
change the visible energy
from ~ 0.8 MeV to ~ 1.8 MeV

Similar signal found for
 ^{215}Po (from ^{235}U chain)
used to model spectra



286 tonne-years of new data,
134 days in 2022/23

using $^{214}\text{Bi}^{214}\text{Po}$ from ^{222}Rn
for β - α scint/reco calibration

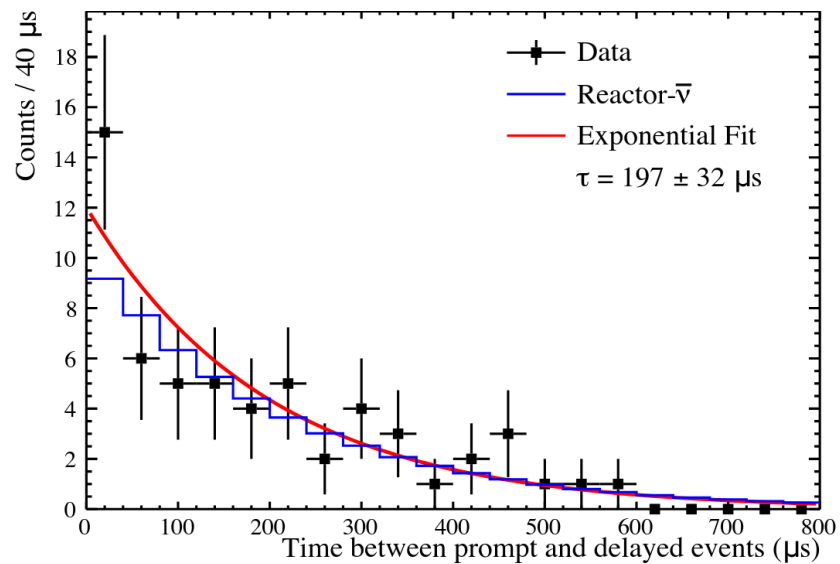
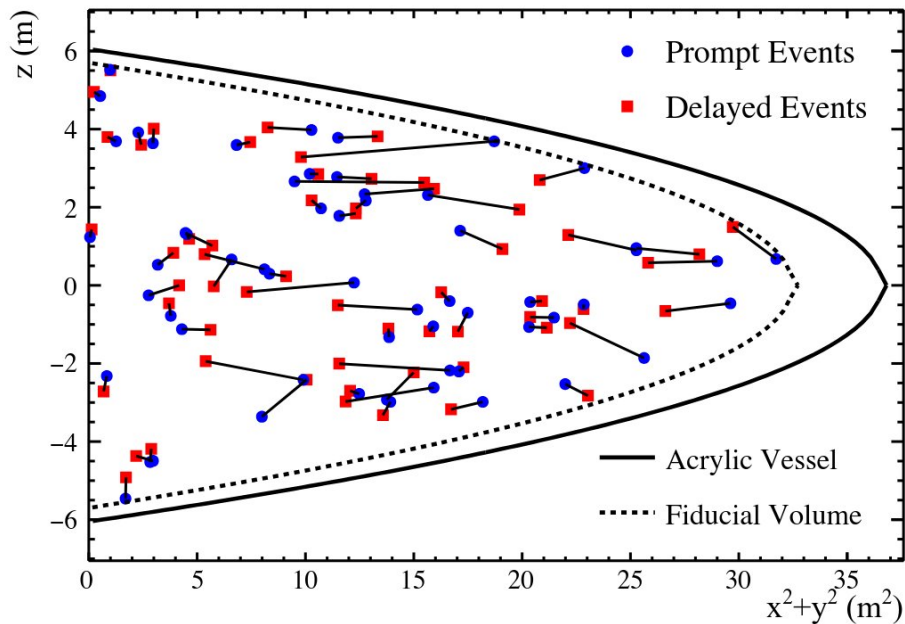
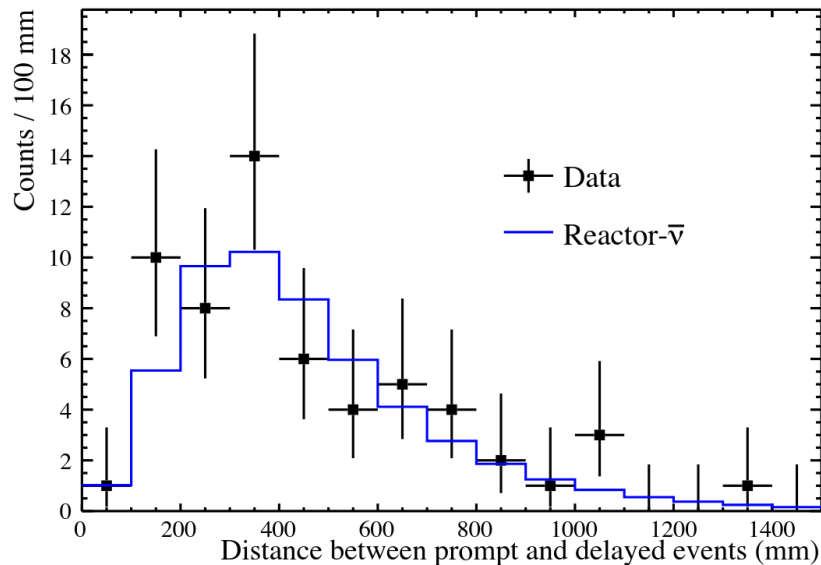
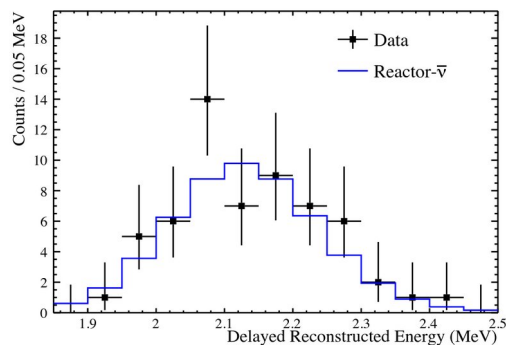
	$^{214}\text{BiPo}$		Reactor- $\bar{\nu}$ IBD	
	Prompt	Delayed	Prompt	Delayed
E (MeV)	1.25-3.0	0.7-1.1	0.9-9.0	1.85-2.5
R (m)	0-4.0	0-4.0	0-5.7	0-5.7
Δr (m)	0-1.0		0-2.5	
Δt (μs)	3.7-1000		0-2000	
LR			>-3.5	

excess of Δt , ΔR coincidences with
prompt events with ^{214}Bi -like energy
delayed events just below 2.2 MeV

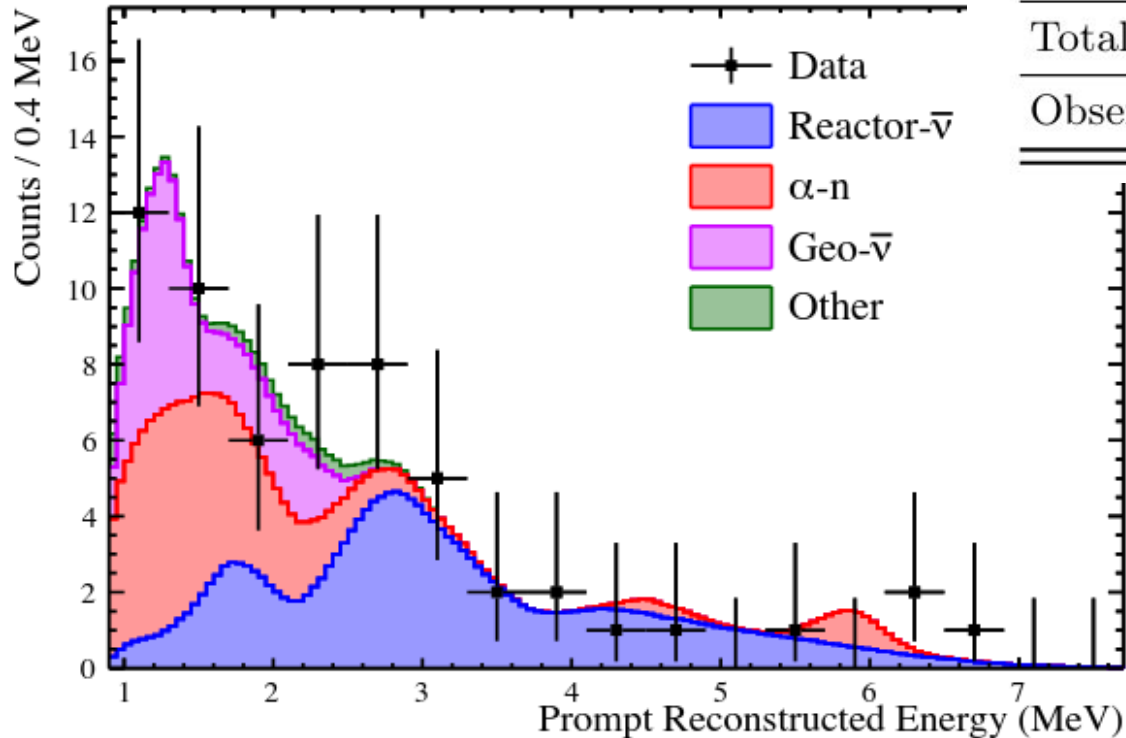
only 1.1 ± 1.1 events expected
in low background data period

IBD candidates

arXiv:2505.04469



antineutrino spectral fitting

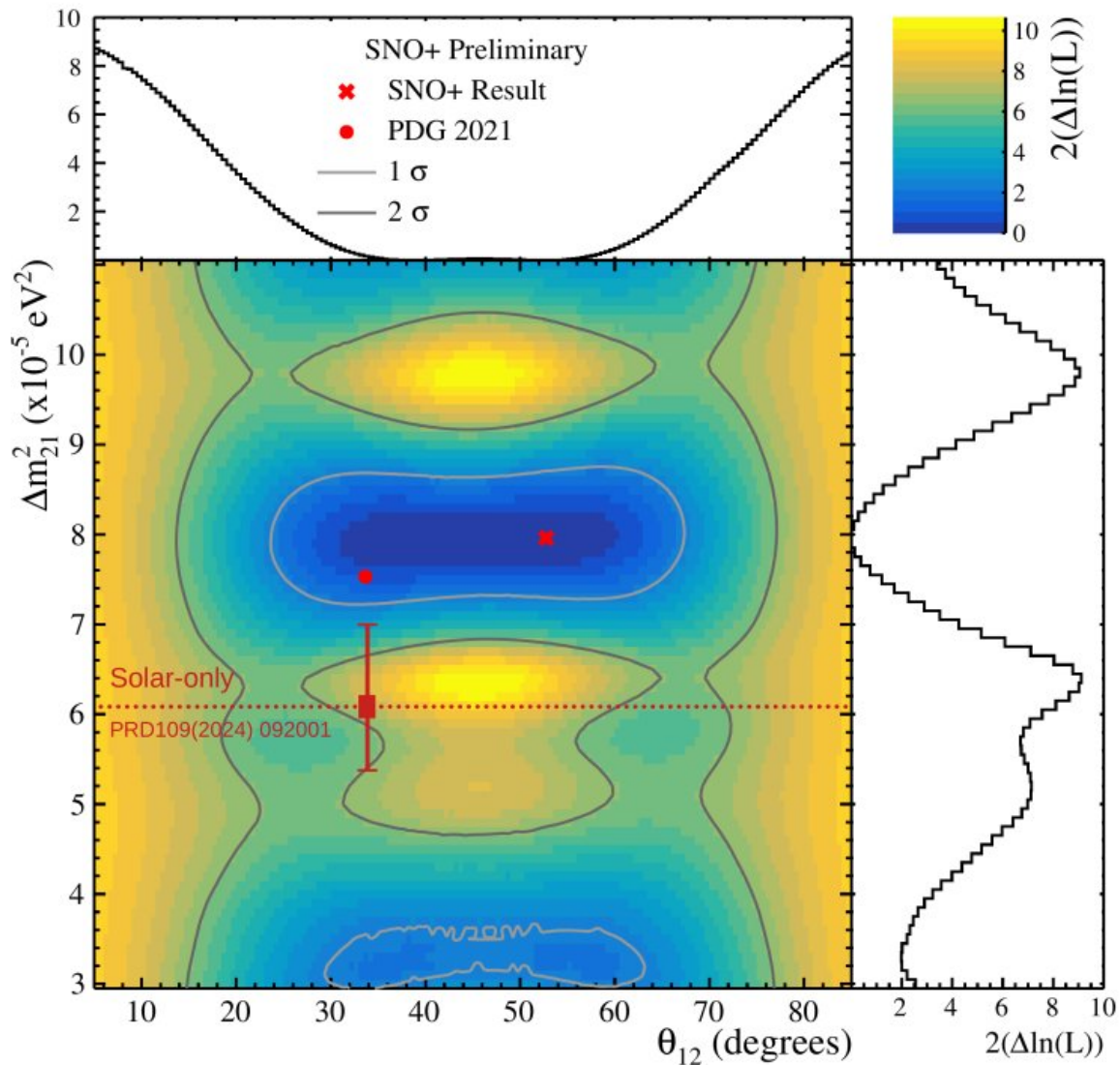
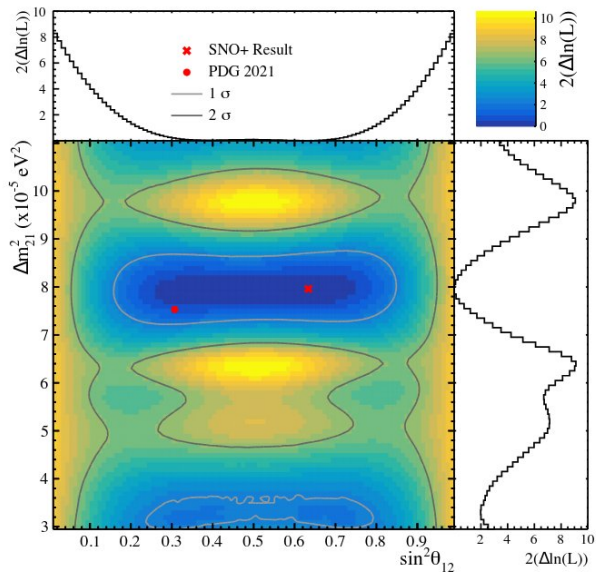


	Expectation	Fit (Uncon.)	Fit (Con.)
Reactor- $\bar{\nu}$ IBD	27.9 ± 0.8	$25.1^{+6.4}_{-2.1}$	27.5 ± 0.9
(α, n)	18.2 ± 5.2	$17.2^{+4.5}_{-4.4}$	$17.2^{+4.5}_{-4.4}$
Geo- $\bar{\nu}$ IBD	7.2	$12.0^{+7.4}_{-6.8}$	$11.1^{+7.1}_{-6.6}$
$^{214}\text{BiPo}$ -like	1.1 ± 1.1	1.2 ± 1.1	1.2 ± 1.1
Accidental	0.3 ± 0.0	0.3 ± 0.0	0.3 ± 0.0
Total	54.7	55.8	57.3
Observed	59	59	59

- accidental coincidences negligible
- robust model of BiPo with proton scatter
- reduced (α, n) model uncertainties
30% g.s. and 100% in e.s.
- detecting the geoneutrino signal
- fit reactor antineutrino oscillation
 1. without external constraints
 2. with global result for combination

antineutrino oscillation fits

	Fit (Uncon.)	Fit (Con.)
Δm_{21}^2 ($\times 10^{-5} \text{eV}^2$)	$7.96^{+0.48}_{-0.42}$	$7.58^{+0.18}_{-0.17}$
$\sin^2 \theta_{12}$	$0.62^{+0.16}_{-0.40}$	0.308 ± 0.013
Geo- $\bar{\nu}$ IBD rate (TNU)	79^{+49}_{-44}	73^{+47}_{-43}



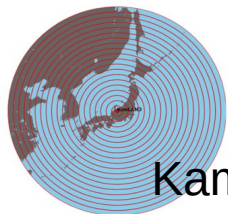
present and future

Now analysing more data already collected:

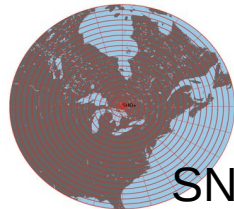
- 50% higher light-yield from bis-MSB
- improved background modeling
- (α, n) discrimination from p-scatter timing
- preparing internal calibration with AmBe

New tools most important for geoneutrinos

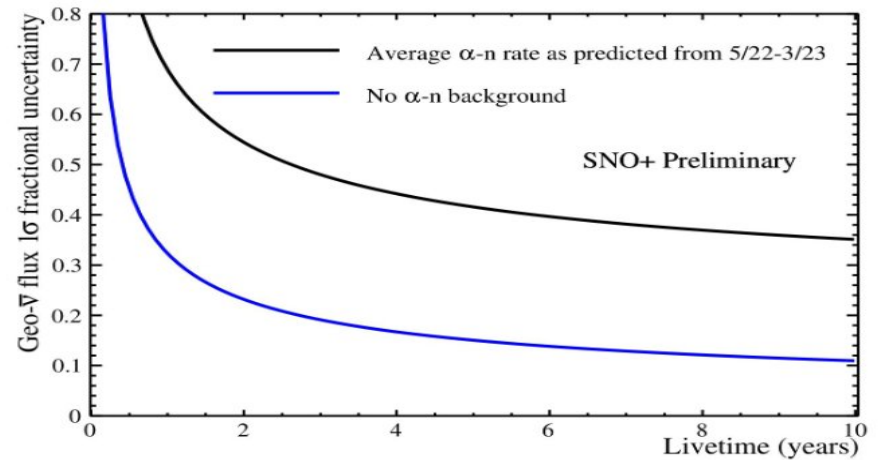
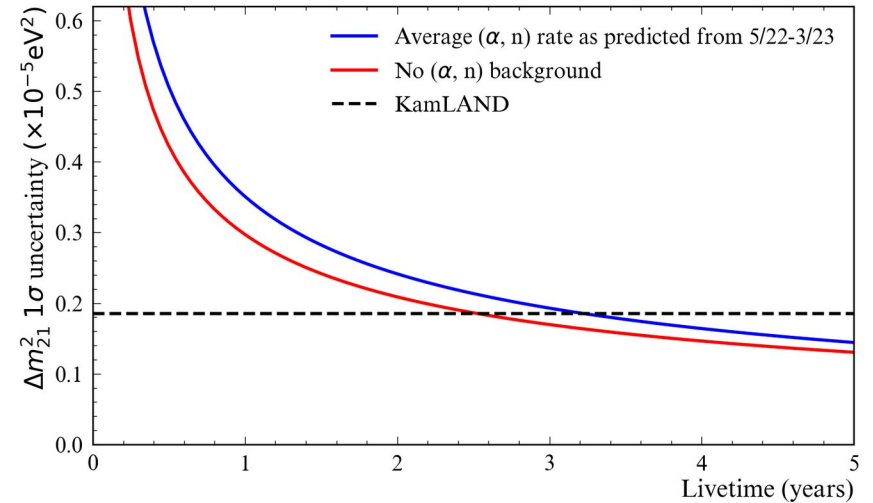
SNO+ does the 3rd measurement with higher crust component than KamLAND and Borexino (or JUNO) to help measure the Earth's mantle



Kamioka



SNOLAB



Summary

SNO+ measures antineutrinos in all its phases

First measurement of antineutrinos from distant reactors in pure water in 2023

Second measurement of antineutrinos from distant reactors in scintillator in 2025

- second-most precise value of $\Delta m_{12}^2 = (7.96^{+0.48}_{-0.42}) \times 10^{-5} \text{ eV}^2$

- expect to match KamLAND precision with three years of data

Third measurement of geoneutrinos in a very complementary location

Auxiliary measurements of (α, n) and new α -p scatter backgrounds

Antineutrino measurements will continue during the Tellurium phase