Results from SNO+

Berkeley
UNIVERSITY OF CALIFORNIA

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for the SNO+ collaboration

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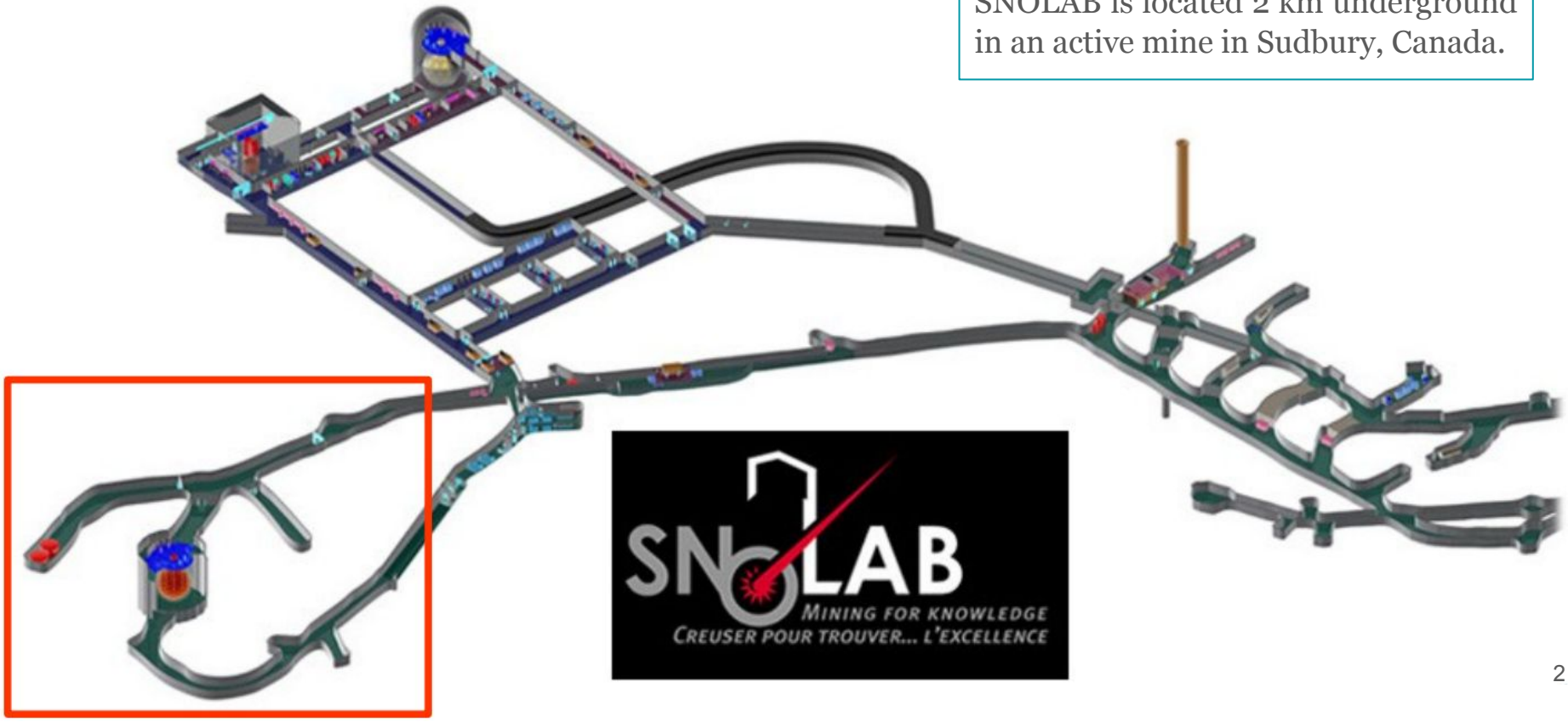
SNOLAB

SNO+ is a multipurpose neutrino experiment in SNOLAB.

SNOLAB is located 2 km underground in an active mine in Sudbury, Canada.



SNO+

Acrylic vessel (radius 6 m)

9394 PMTs

2.5-m buffer (water)

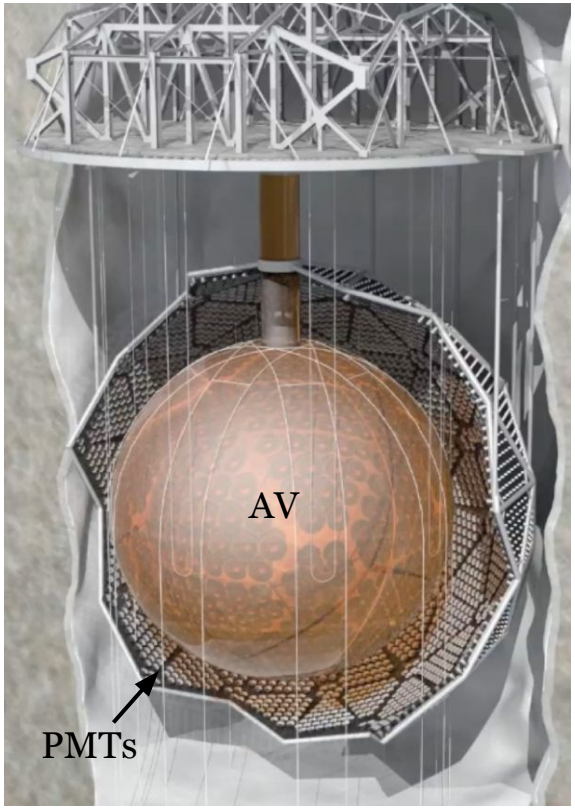
SNO+

Primary goal:
Search for the lepton flavor-violating process of $0\nu\beta\beta$ using Te-loaded liquid scintillator.

- Novel LS approach is readily up-scaled.

Also measuring:

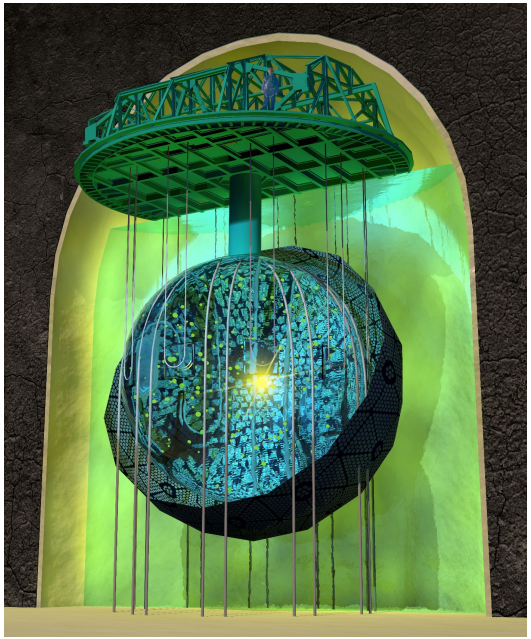
- solar ν (interactions with ^{13}C),
- reactor ν oscillations,
- geo ν flux,
- & watching for supernova ν.



SNO+ scintillators

SNO+ has characterized the detector and backgrounds prior to loading tellurium.

Mass	0.78 ktons
Scintillator	LAB + PPO (2.2 g/L) + BHT (5.5 mg/L) + bis-MSB (2.2 mg/L) + {Te(0.5%)-ButaneDiol + DDA(0.2%)}
Radiopurity (no Te)	^{238}U: 4×10^{-17} g/g, ^{232}Th: 5×10^{-17} g/g
Energy Resolution	6.5% @ 1 MeV
Position Resolution	12 cm in *x,y,z* @ 2.5 MeV
Overburden	2.0 km (~70 μ/day)



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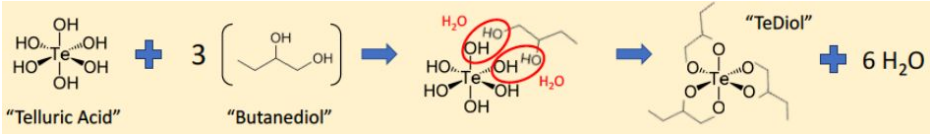
2022/5 - 2023/3
Results presented here

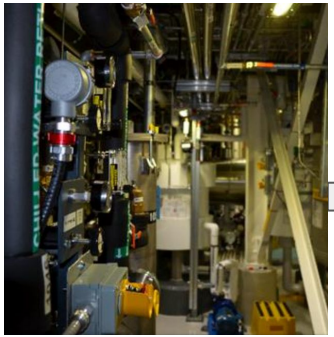
2023/12 - present
Results forthcoming

2025 ...
Preparing to load Te

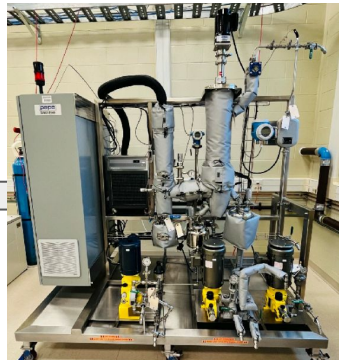
Te-loading



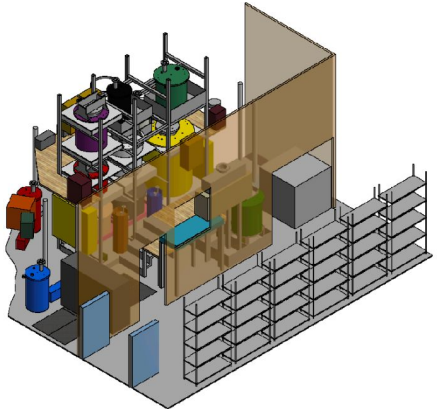
BD purification (UG)
Commissioned



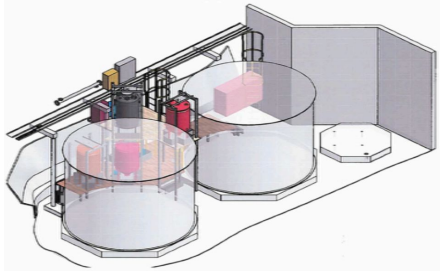
DDA distillation (surface)
Commissioned



Te acid purification (UG)
Commissioned



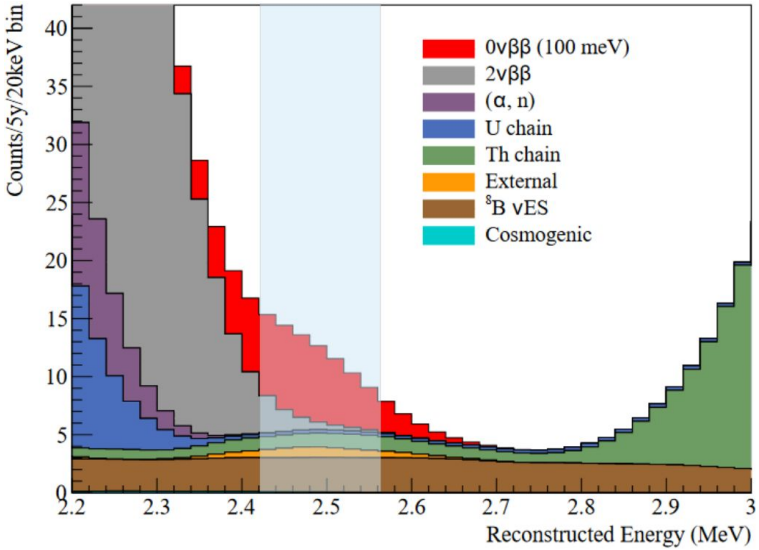
Te-BD synthesis (UG)
Commissioning



Detector (UG)

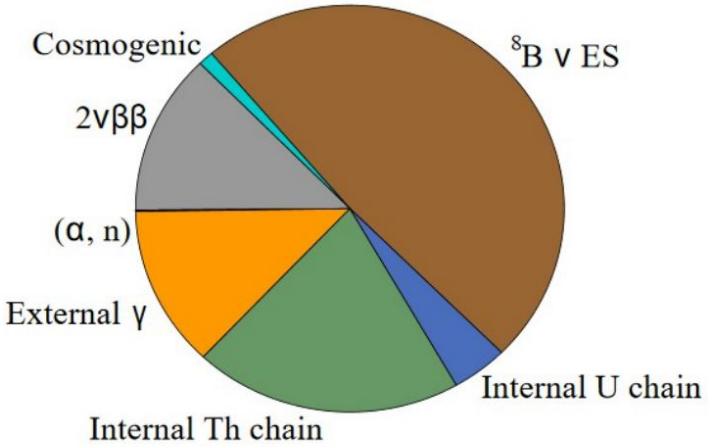
$0\nu\beta\beta$ search with 0.5% Te

SNO+ will look for **$0\nu\beta\beta$ events** at the endpoint of the **double beta decay spectrum**.



Backgrounds

ROI: 2.42-2.56 MeV [-0.5σ - 1.5σ], 3.3 m FV, 9.47 counts/yr.



$0\nu\beta\beta$ sensitivities

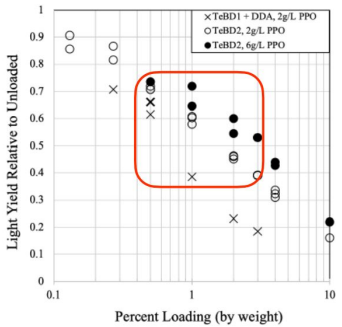
Initial 0.5% Te

A 5-year counting analysis of 1330 kg of ^{130}Te yields $T^{0\nu}_{1/2} > 2 \times 10^{26}$ yr (90% C.L.).

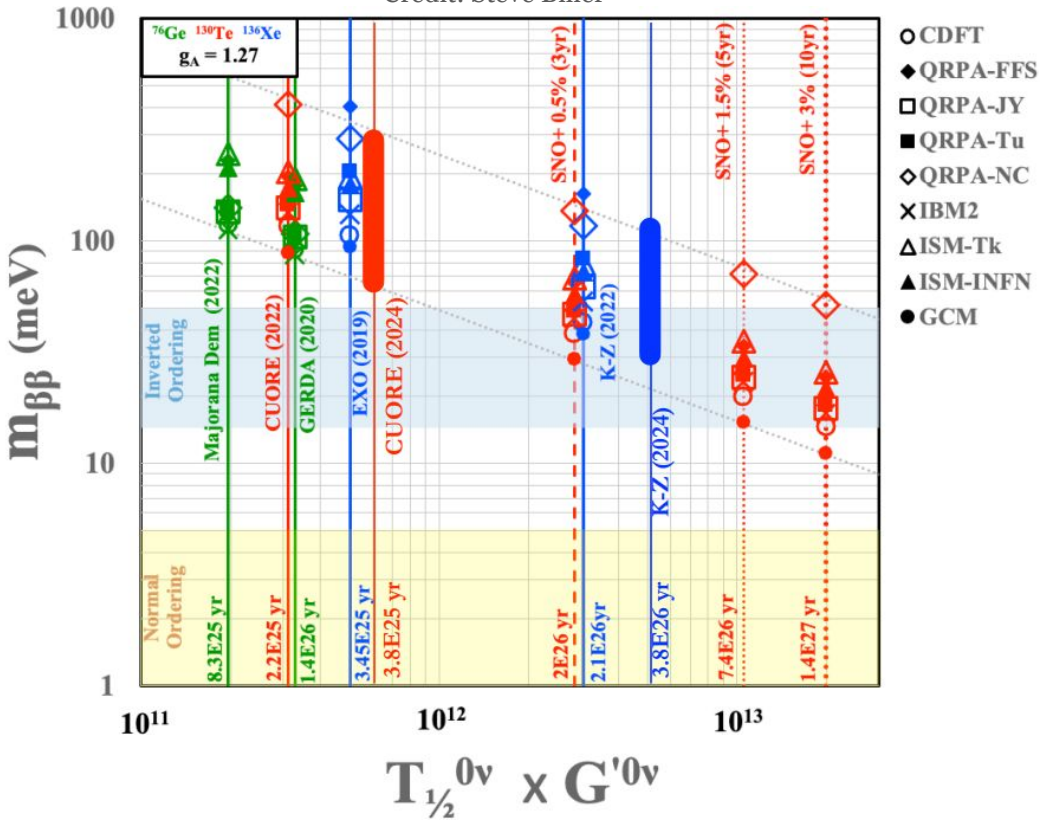
Later 1.5% Te

A 5-year counting analysis of 4000 kg of ^{130}Te yields $T^{0\nu}_{1/2} > 7.4 \times 10^{26}$ yr (90% C.L.).

R&D has shown that Te loading can be increased.



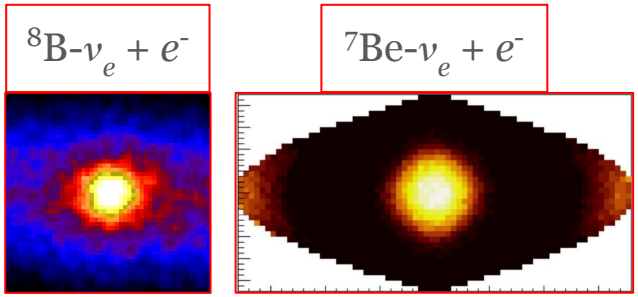
Credit: Steve Biller



$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \qquad m_{\beta\beta} = \left| \sum_{k=1}^{3} m_k U^2_{ek} \right|$$

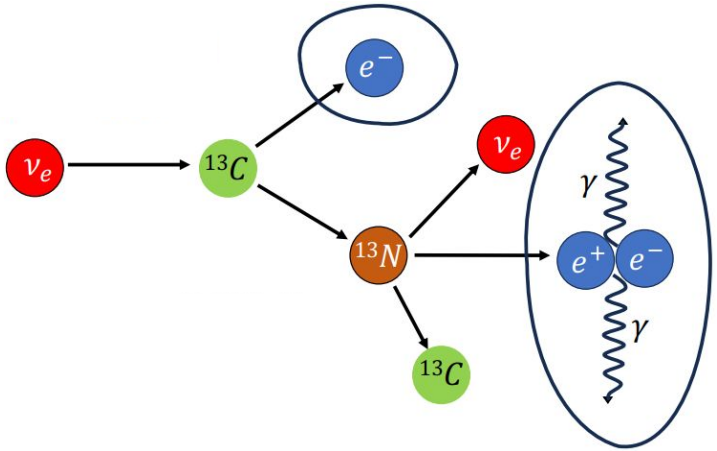
^{8}B solar neutrinos on ^{13}C

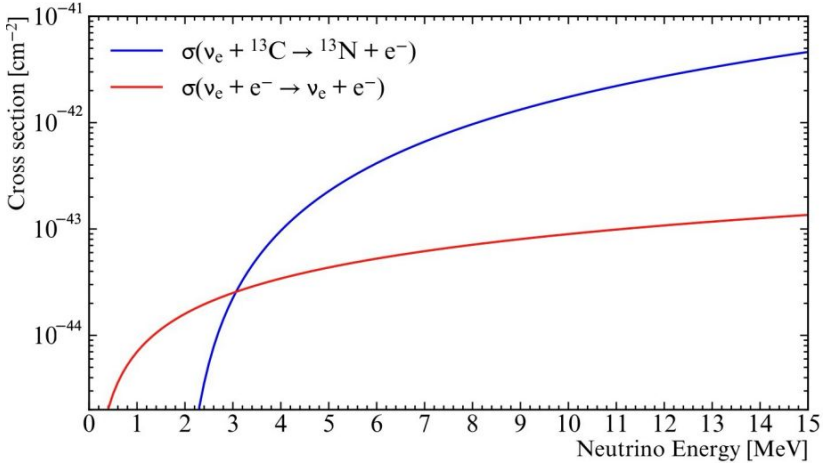
Flux and spectrum are studied with elastic scattering, $\nu_e + e^-$.
A CC interaction on ^{13}C is also possible, but not yet observed.



[Super-K] [Borexino]

Prospects: ^{13}C abundance is 1.1% while cross section is $O(10)$ times larger.
Delayed coincidence of e^- and e^+ helps suppress backgrounds, though $\tau_{1/2}$ = 10.0 min.
Expect 17 CC interactions per year in SNO+.

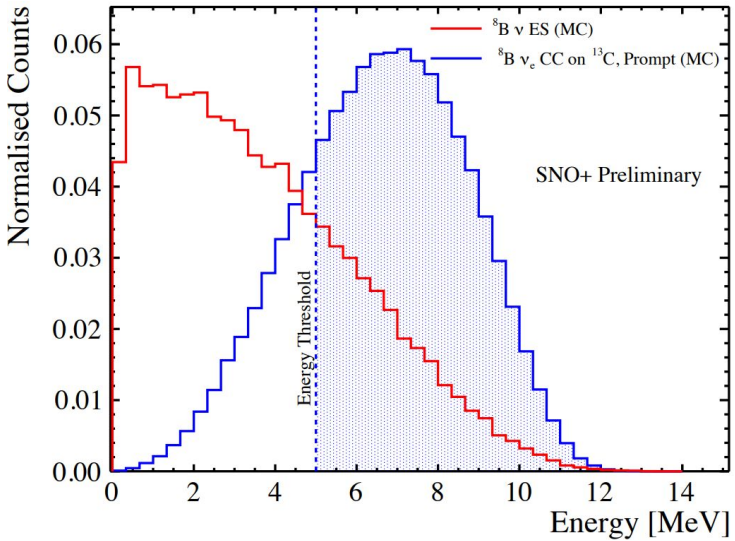


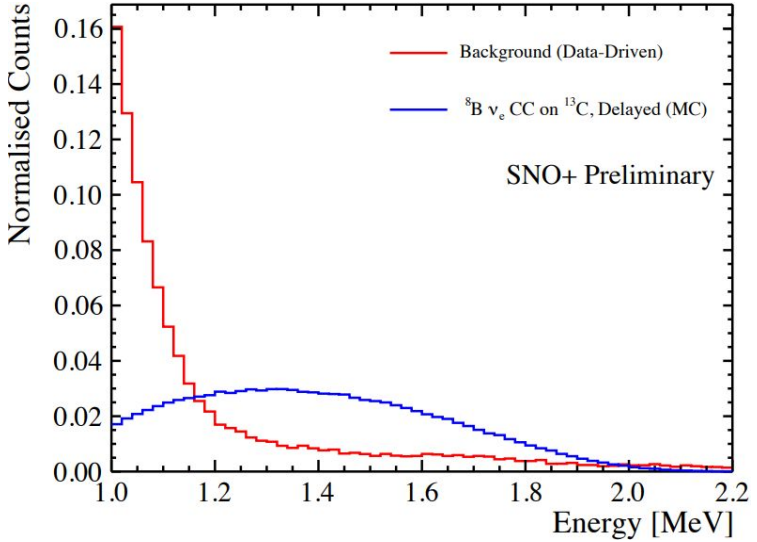


^{8}B solar neutrinos on ^{13}C

Prompt e^{-} energy = E_{ν} – 2.2 MeV
Selecting events above 5 MeV leaves ^{8}B elastic scatters as the sole background to prompt events.

Delayed e^{+} plus 1.0-MeV annihilation γ energy: [1.01, 2.20] MeV. Background dominated by ^{210}Bi below 1.2 MeV.





^{8}B solar neutrinos on ^{13}C

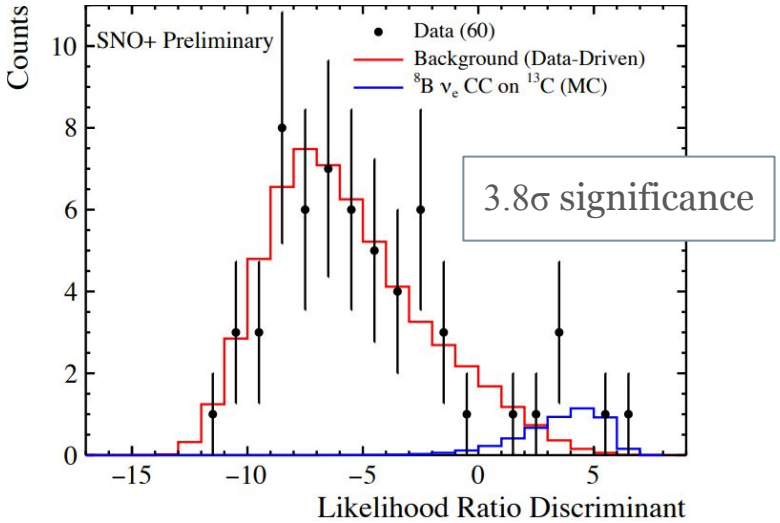
Cosmogenic backgrounds are small at SNOLAB's great depth.

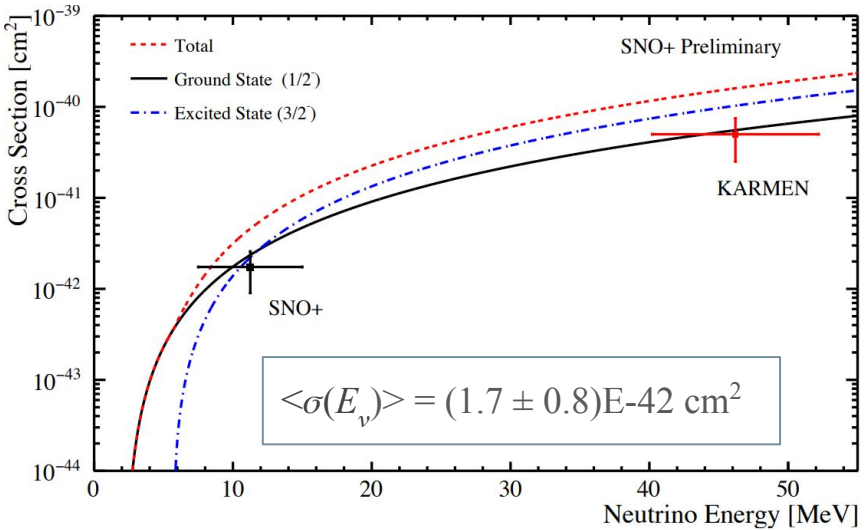
With 225 days of data, 4 signal-like coincidences were observed.

Box Cuts	Prompt	Delayed
E (MeV)	5.0-15	1.14-2.20
R (m)	0-5.3	0-5.3
Δr (m)	0-0.36	
Δt (min)	0.01-24	

A likelihood ratio is also built with these parameters.

LAB + PPO (2.2 g/L)



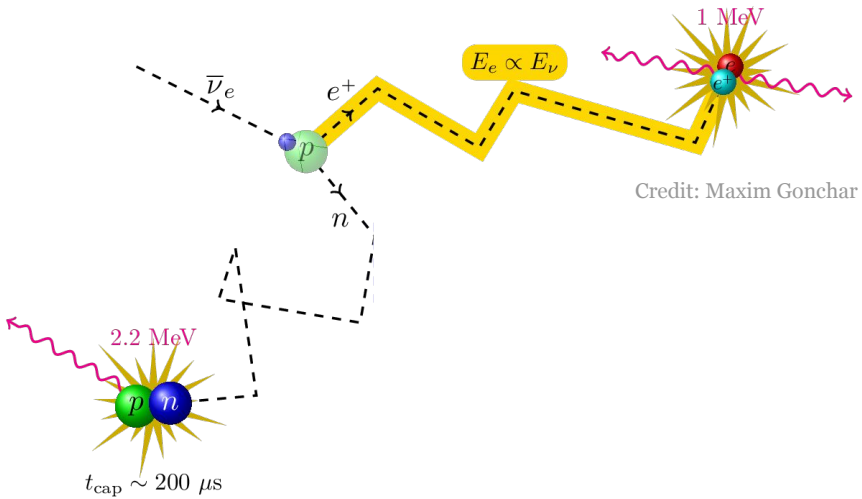


Antineutrinos at SNO+

Detected using inverse beta decay (IBD) on H:

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- Prompt energy spectrum closely follows the E_ν.
- Delayed energy spectrum is a 2.2-MeV γ peak.



Credit: Maxim Gonchar

Sources
- Reactor
- Geo

Backgrounds
- (α,n) reactions
- ^{214}BiPo-like (*new observation*)
- Accidentals from ambient radio.
- Atmospheric neutrinos
- Muon-induced
  - Fast n
  - β-n decays

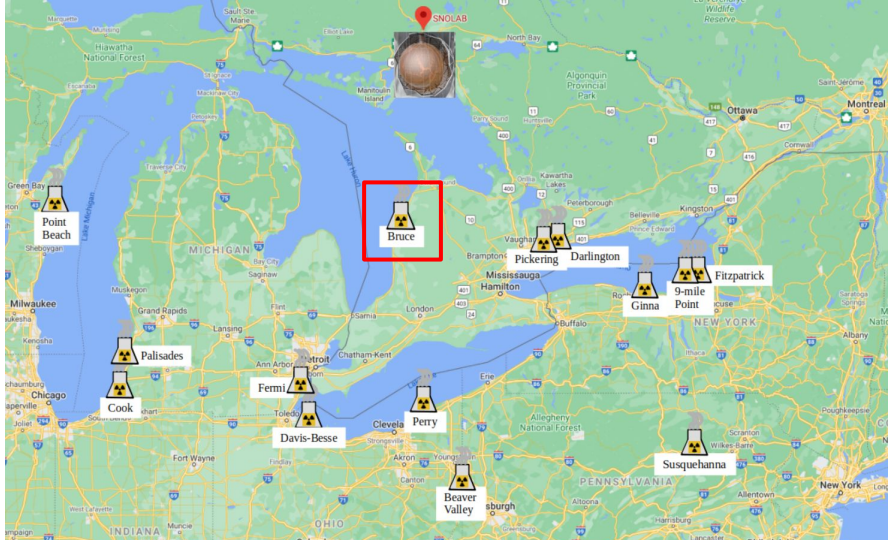
	^{214}BiPo		Reactor-$\overline{\nu}$ IBD	
	Prompt	Delayed	Prompt	Delayed
E (MeV)	1.25-3.0	0.7-1.1	0.9-9.0	1.85-2.5
R (m)	0-4.0	0-4.0	0-5.7	0-5.7
Δr (m)	0-1.0		0-2.5	
Δt (μs)	3.7-1000		0-2000	

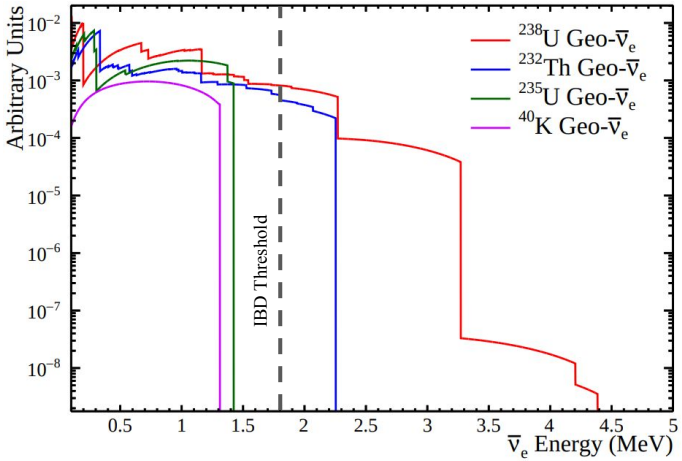
Sources

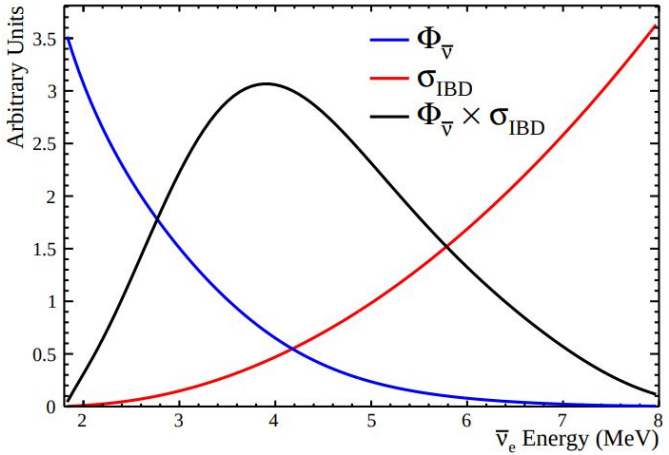
The nearest reactors are the Bruce complex, 240 km away, one of the largest & most powerful sets.

- The average distance traveled by detectable reactor neutrinos is about 620 km.

Reactor power information is publicly available for cores across the world.







(Anti)neutrino oscillation

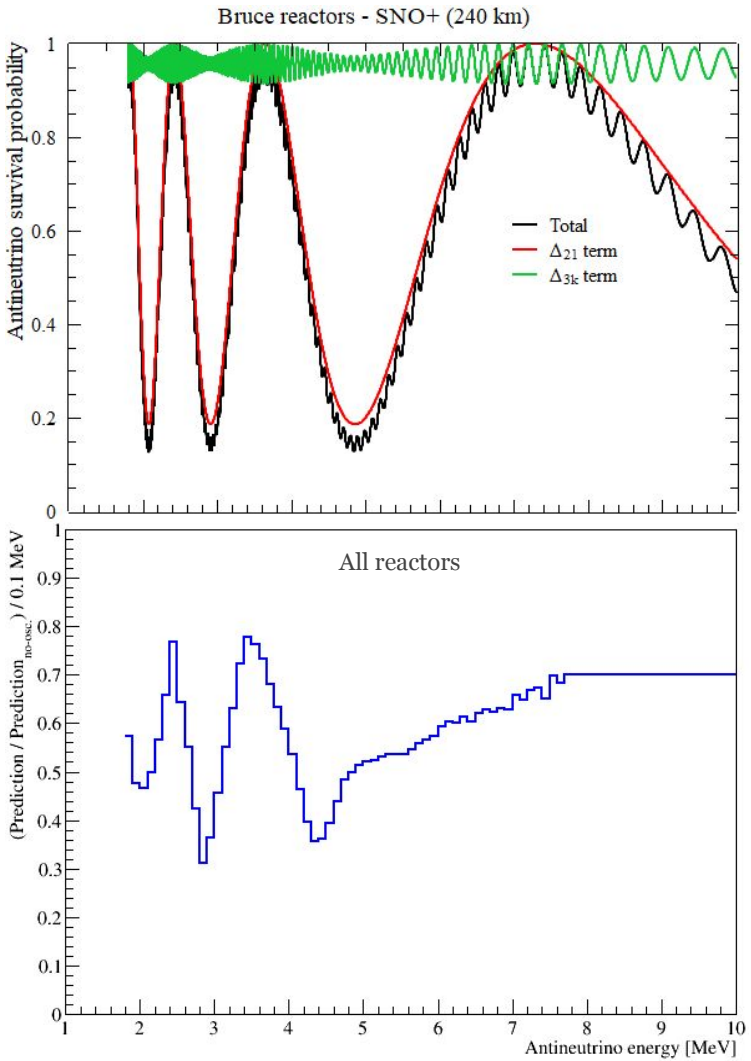
The probability that an electron (anti)neutrino does not oscillate into another flavor depends on

- oscillation angles $\boldsymbol{\theta}_{ij}$
- difference between mass-squares Δm^2_{ij}
- distance traveled L
- energy of the neutrino E_ν

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\Delta_{ij} \equiv 1.267\Delta m^2_{ij} L/E_\nu$$

Approximately 100 reactor-ν IBDs are expected within the AV per year.
And about 25 geo-ν IBDs per year.
The matter effect is taken into account and found to induce a change in the flux of $O(1\%)$ or less.

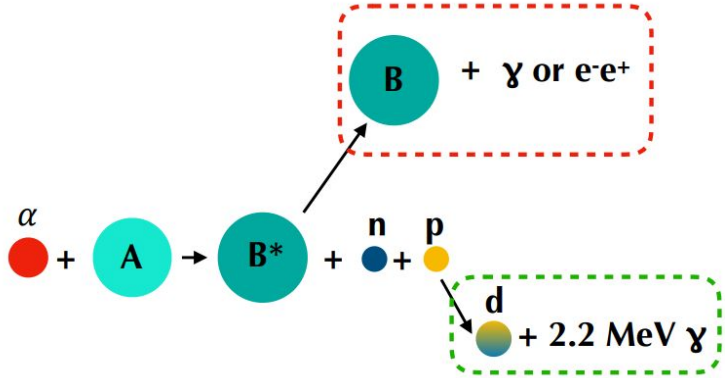


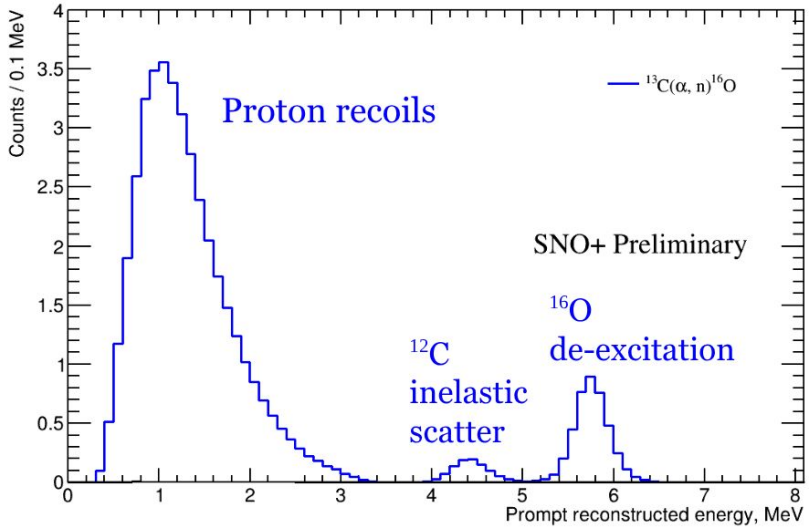
(α,*n*) background

The (α, *n*) background originates from the naturally occurring ^{210}Po α-decays in which the α particles interact with ^{13}C in the scintillator.

The ^{13}C(α, *n*)^{16}O reaction produces three distinct energy peaks.

Fitting the prompt energy spectrum produces uncertainties smaller than the initial constraints ⇒ SNO+ expects to make useful measurements of the ^{13}C(α, *n*)^{16}O reaction.





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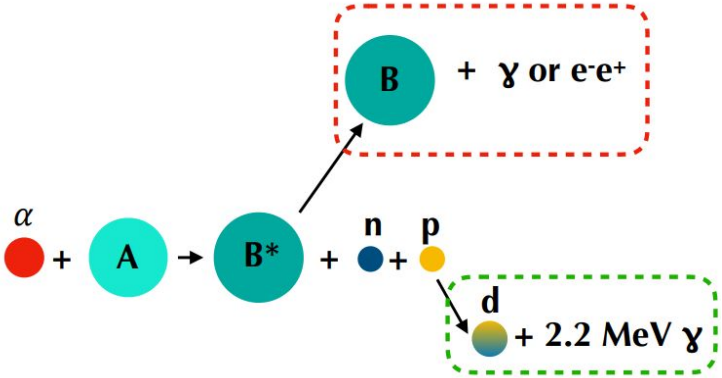
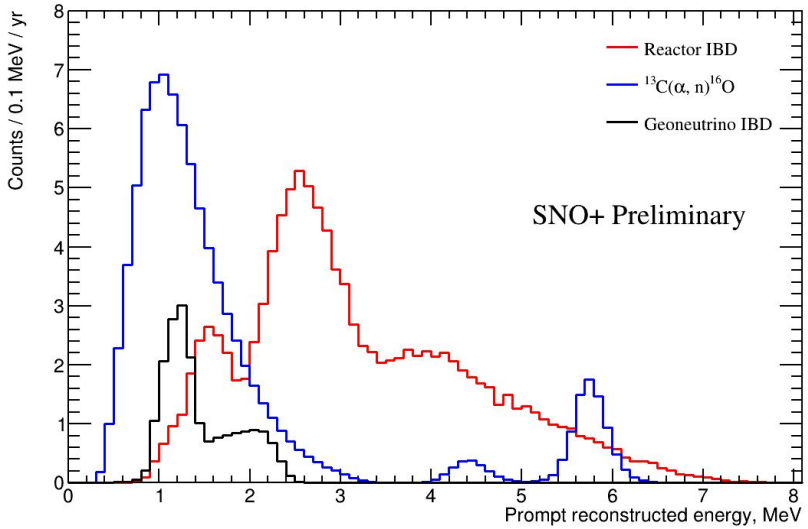
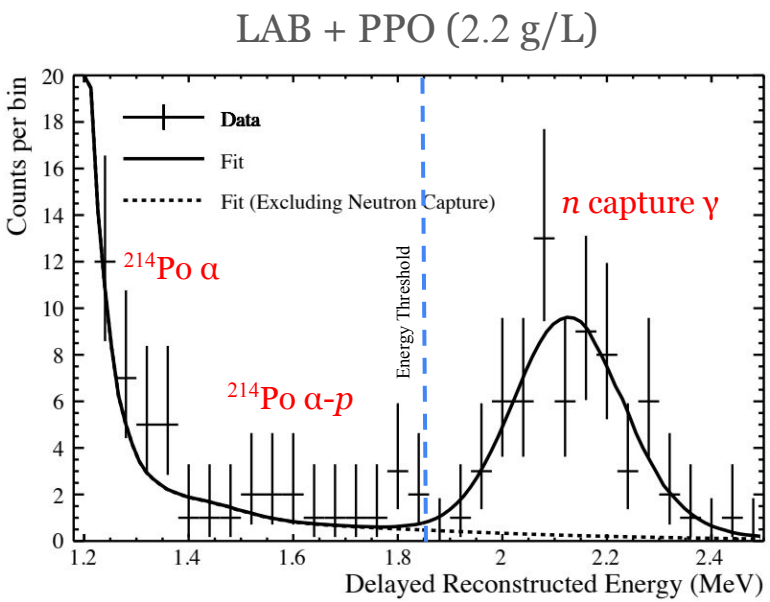




^{214}BiPo-like background

- An excess of coincidences is observed with delayed event energies just below the 2.2-MeV ROI. The Δt, Δr, & prompt E distributions are consistent with ^{214}BiPo β-α decays.
- These tails are suspected to arise from α-p elastic scatters. More scintillation is produced than by α's alone due to lesser quenching of p's.
  Rare α + γ decays are too low in E & rate to create excess.
- A data-driven model of the ^{214}Po energy spectrum is created using a kernel density estimation of the ^{215}Po energy distribution and fitted to the ^{214}Po distribution.

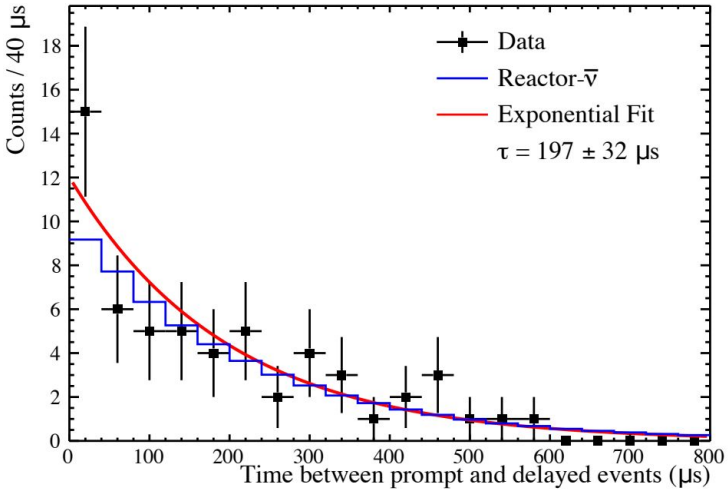


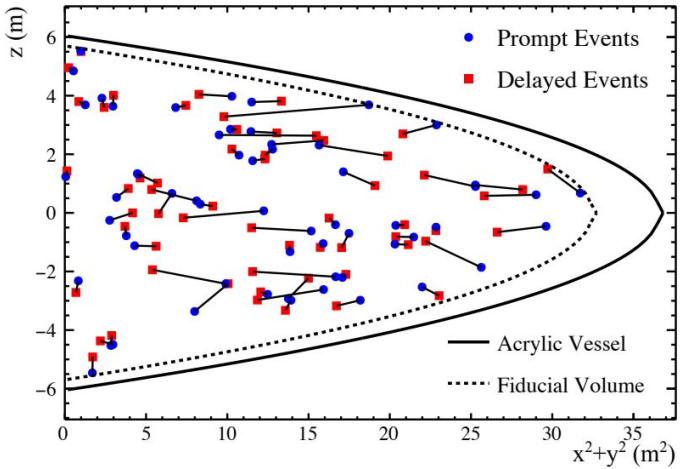
Observables

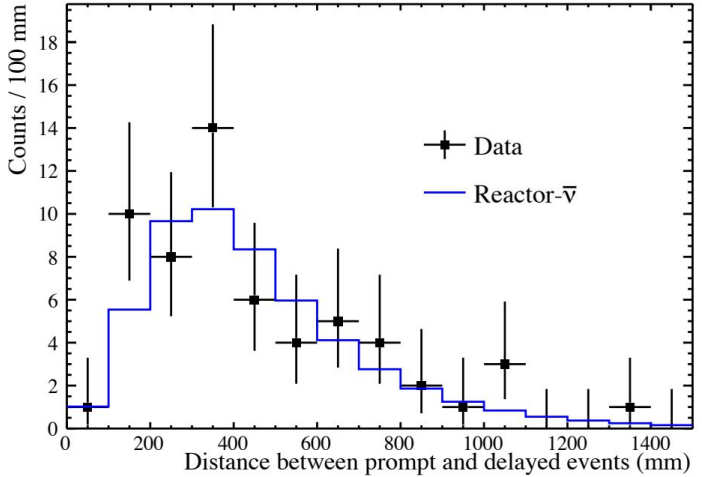
134.4 days of data

LAB + PPO (2.2 g/L)

	Expectation
Reactor-$\bar{\nu}$ IBD	27.9±0.8
(α, n)	18.2±5.2
Geo-$\bar{\nu}$ IBD	7.2
^{214}BiPo-like	1.1±1.1
Accidental	0.3±0.0
Total	54.7
Observed	59

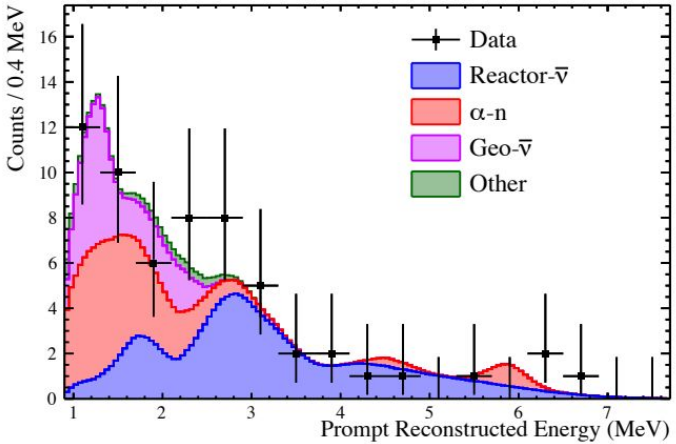


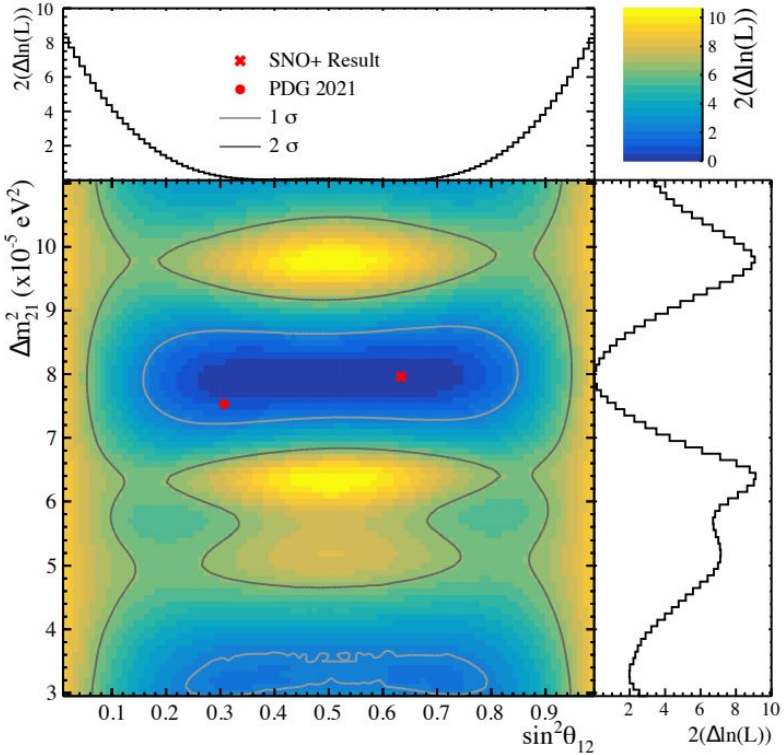




Spectral analysis

- Second-most precise measurement of $\Delta m^2_{21} = (7.96^{+0.48}_{-0.42}) \times 10^{-5}$ eV^2.
  - Tension between solar and reactor Δm^2_{21}, after combining SNO+ & KamLAND, slightly > 1.5σ.
  - With ~3 years of data, SNO+ will provide a measurement as precise as KamLAND (~2%).





- First measurement of geo-nu IBD rate in the Western hemisphere (3rd ever): 73^{+47}_{-43} TNU.

Summary

SNO+ is preparing to load Te into liquid scintillator.

SNO+ is characterizing the detector & backgrounds, and studying neutrinos.

Using LAB + PPO (2.2 g/L) data:

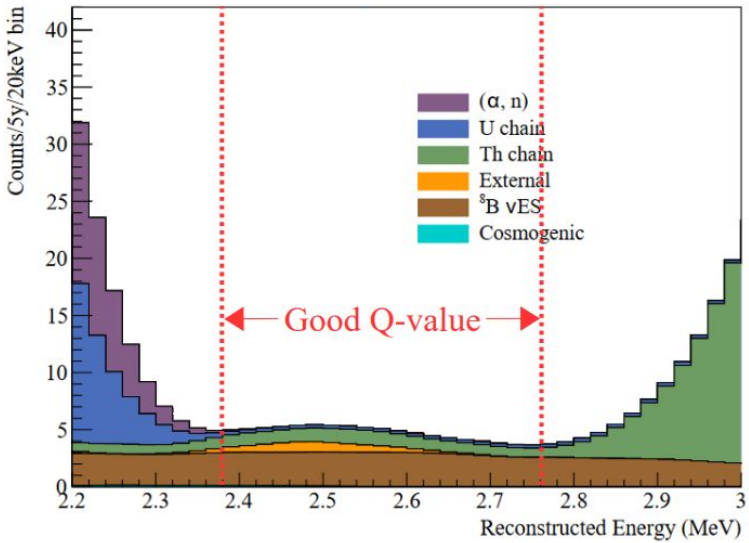
- First observation of solar neutrino CC interactions on ^{13}C, owing to the low cosmogenic backgrounds at SNOLAB.
- Second-most precise measurement of Δm^2_{21}.
- Third measurement of the geo-neutrino flux, first in the Western hemisphere.
- First identification of a ^{214}BiPo-like background (suspected α-p) that can be important for past & future IBD measurements.
- Watching for a supernova.

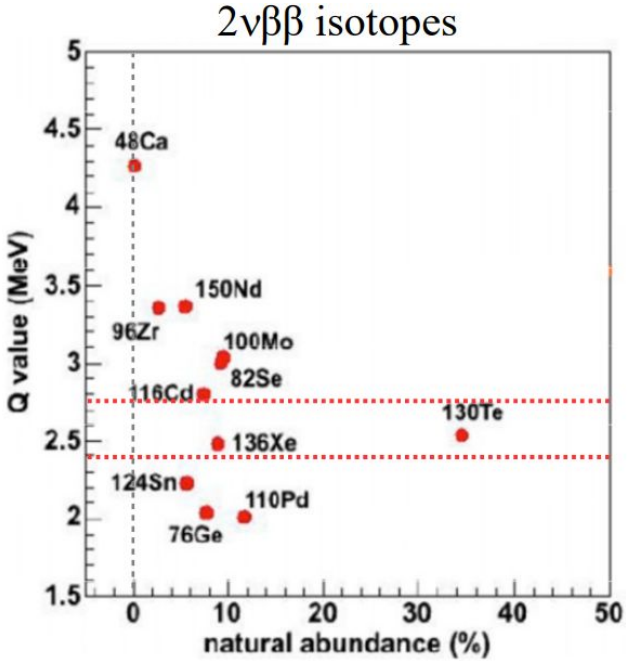
All measurements are improving with additional data.

$2\nu\beta\beta$ decay in scintillator

Need a $2\nu\beta\beta$-decay isotope with a favorable Q-value.

Backgrounds (SNO+)



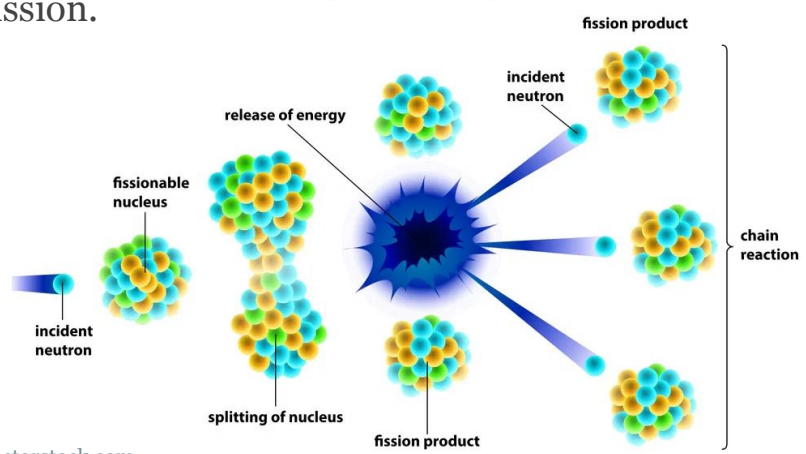


Reactor antineutrinos

Reactors are a highly intense and pure source of electron antineutrinos (anti-ν_e).

$\approx 2\times10^{20}$ s^{-1} GW^{-1}.

Four primary fissile isotopes (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) produce neutron-rich daughters that undergo β decay, yielding about six anti-ν_e per fission.



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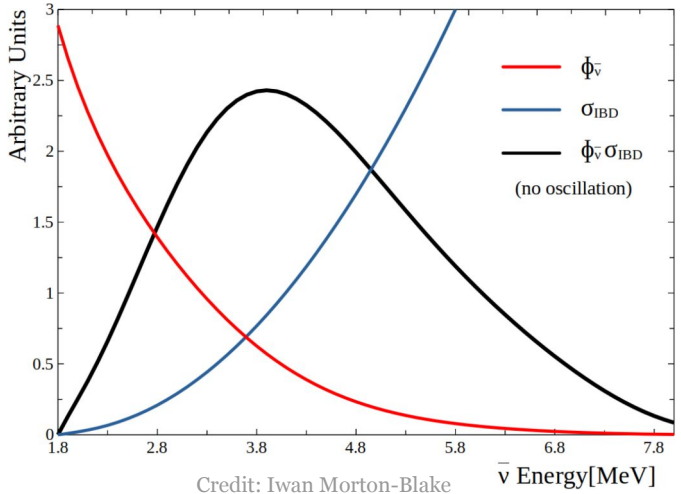
Their energy spectra are reasonably well understood and are continuing to be measured with increasing accuracy.



Credit: Iwan Morton-Blake

Reactor IBDs at SNO+

About **39%** of IBDs originate from Bruce (**240 km**) and 18% from two other Canadian complexes at 340 and 350 km.