Antineutrinos in SNO+

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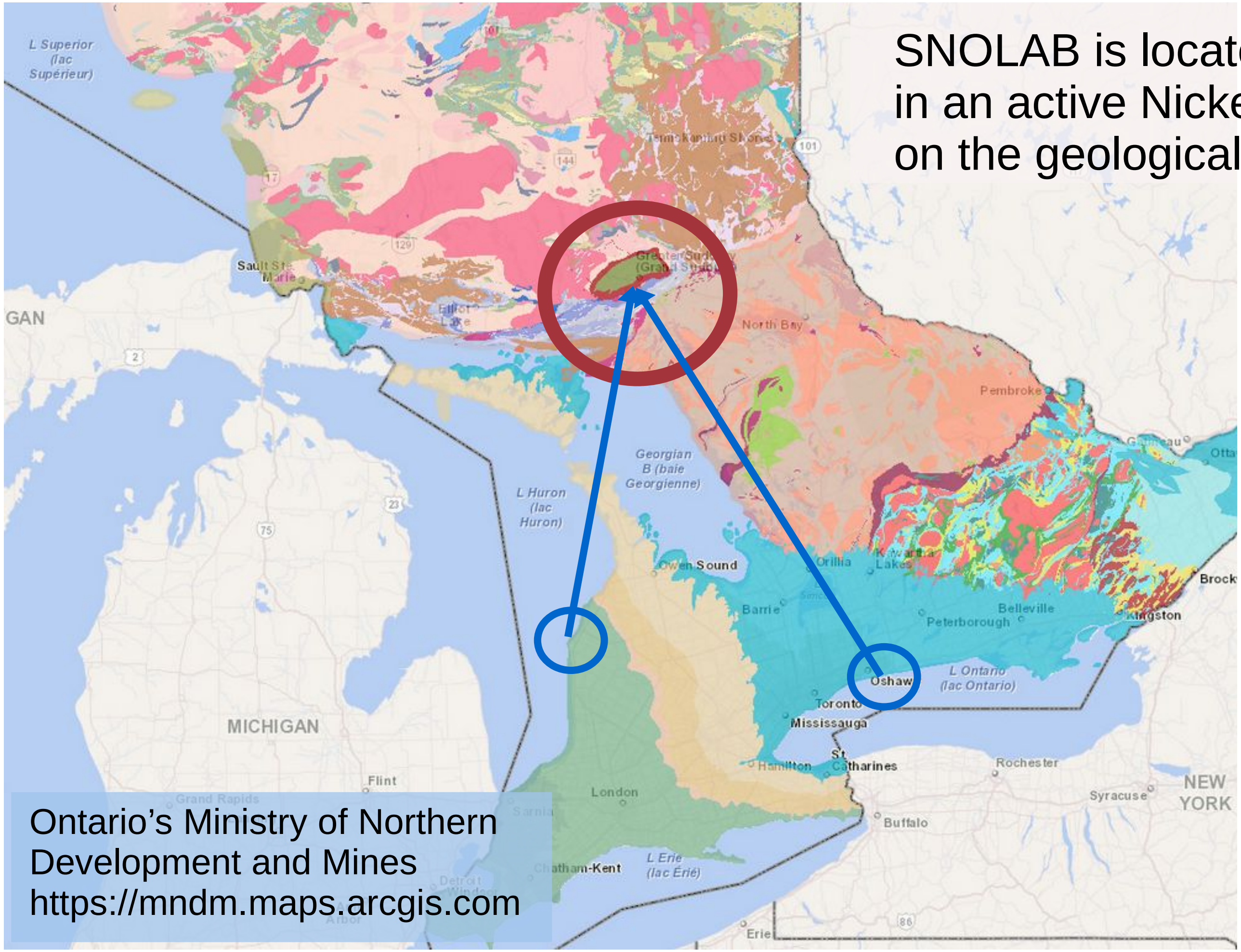
on behalf of the
SNO+ Collaboration

Applied Antineutrino Physics Workshop
York, UK, September 2023

https://snoplus.ca

https://lip.pt

antineutrinos at SNOLAB



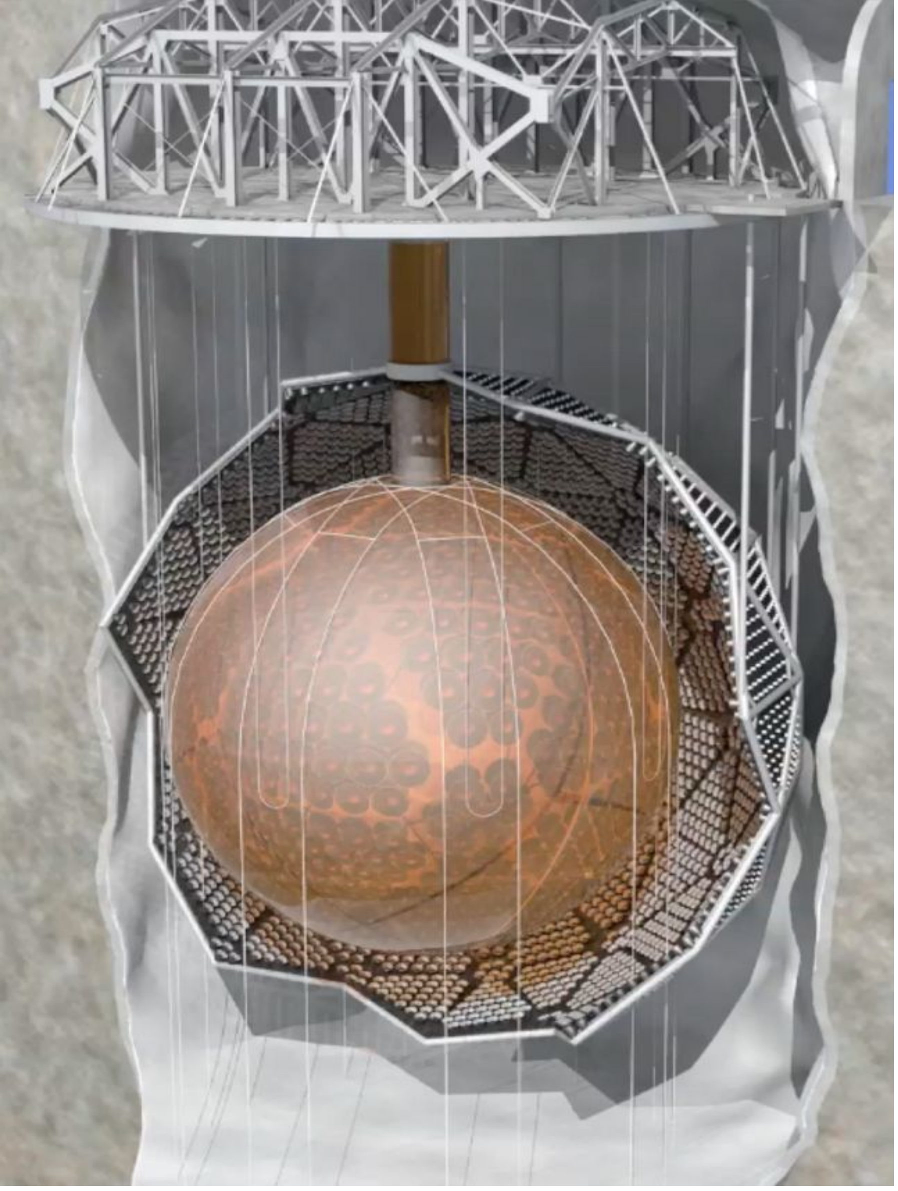
Ontario's Ministry of Northern Development and Mines
https://mndm.maps.arcgis.com

SNOLAB is located 2 km underground (6 km w.e.)
in an active Nickel mine (also Co, Cu, Pt, Pa, Au)
on the geologically interesting Sudbury impact basin

Geoneutrinos from the thick crust
of the North–American plate
a new location to add to
KamLAND (Japan) + Borexino (Italy)

Antineutrino from CANDU -
Pressurized Heavy Water Reactors

with clear oscillation features
to add more precision to Δm^2_{12}
from KamLAND + solar neutrinos



the SNO+ detector

2070 m underground (can veto ~ 3 muons / hour)

> 9000 PMTs @ 8.5 m (50% optical coverage)

changing active medium H_2O to liquid scintillator
inside 6.0 m radius (5.5 cm thick) acrylic vessel

1. Water Phase (from September 2017 to July 2019)

2.2 MeV gamma Cherenkov O(10 PMT hits)

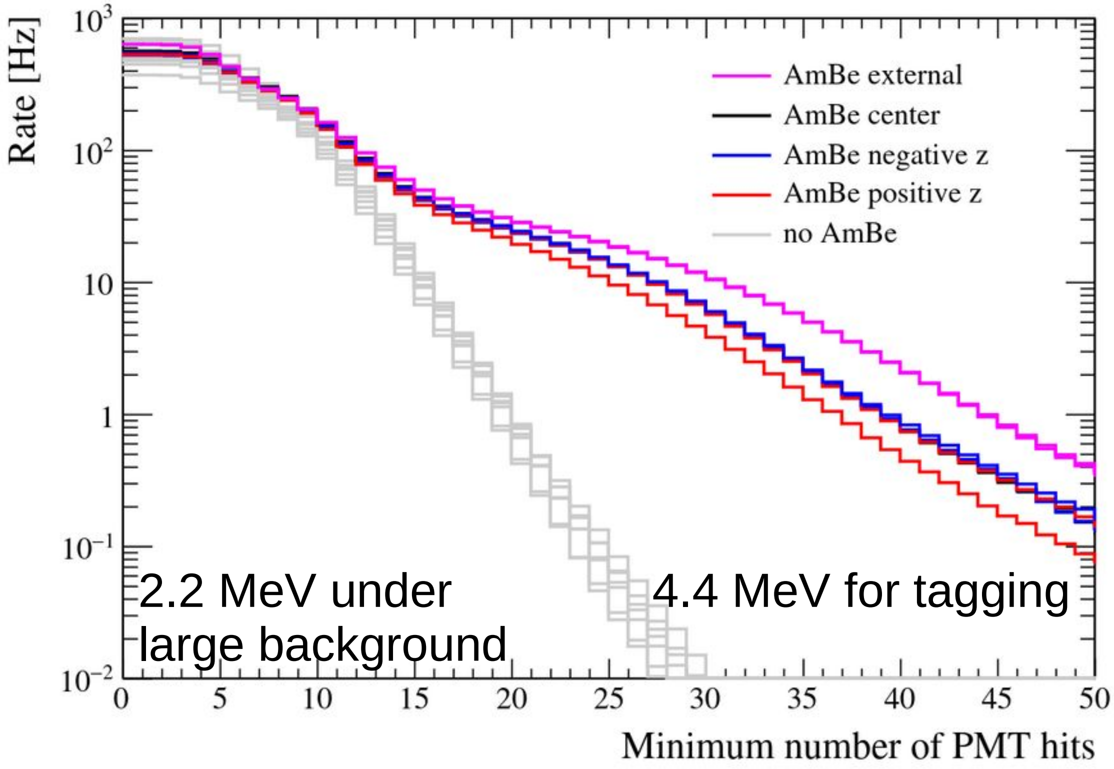
2. Partial Fill (from March to October 2020)

3. Scintillator Phase (from May 2021)

^{130}Te ββ

2.2 MeV gamma Scintillation O(1000 PMT hits)

2.2 MeV and 4.4 MeV in water



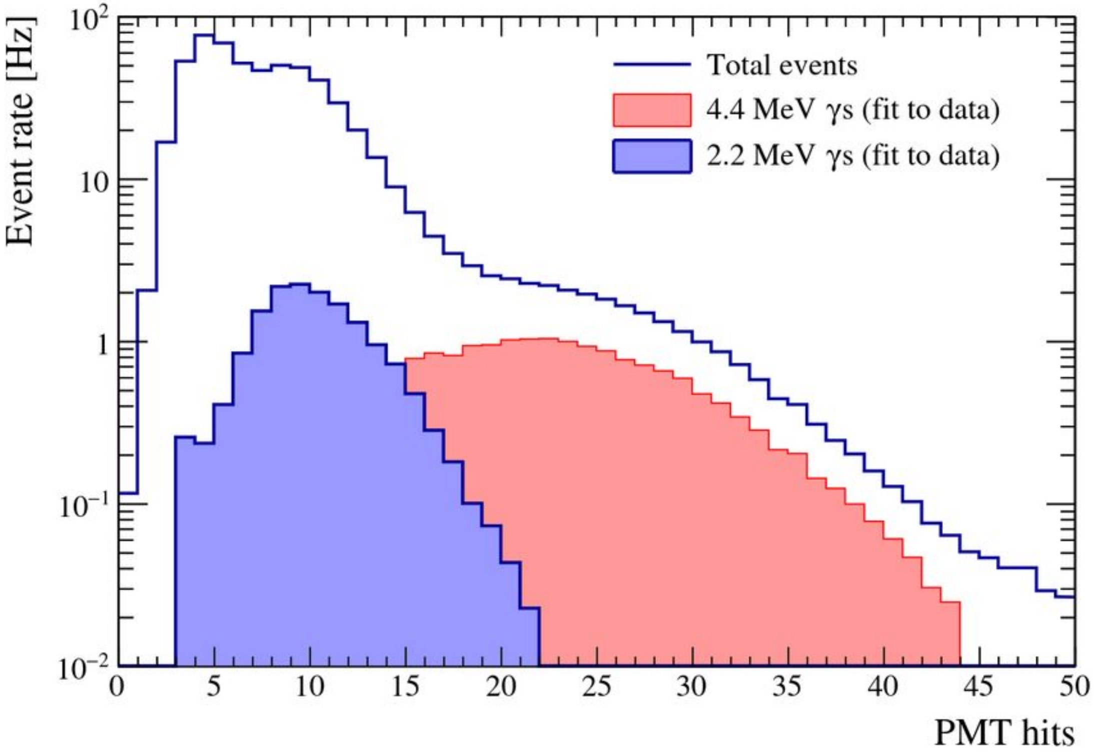
AmBe:
~60 Hz antineutrino calibration source!

Prompt 4.4 MeV gamma (Eff ~100%)
Delayed 2.2 MeV gamma (at threshold)
- calibration of the trigger efficiency

Delayed coincidences in time and space
- calibration of the neutron propagation
- measurement of the p-n cross-section

Both signals can be *statistically* seen

2.2 MeV and 4.4 MeV in Water



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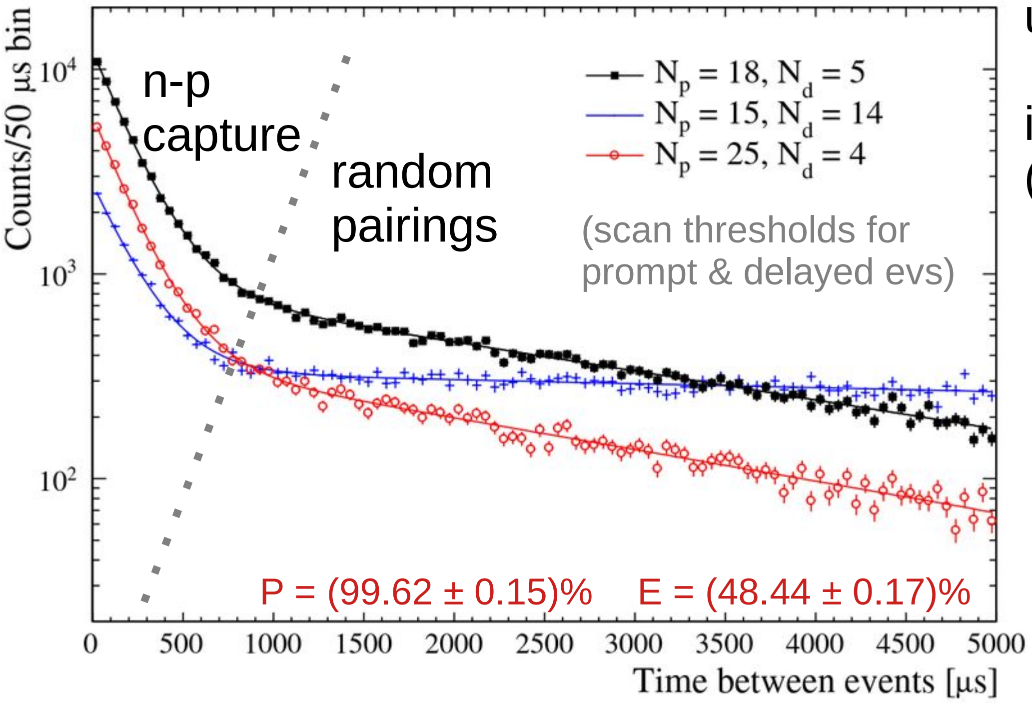
cross-section for n-p capture



using only PMT hits and time, no reconstruction

identify two competing coincidence processes (from two exponentials in event time difference)

- slow random coincidences from high rates
  * 2.2 MeV trigger efficiency, E ~50% *
  (w/ 4.4 MeV tagging purity, P~100%)

- fast neutron capture time constant
  * neutron-proton capture cross-section *
  $\tau = \lambda^{-1} = (207.03 \pm 0.42)$ μs

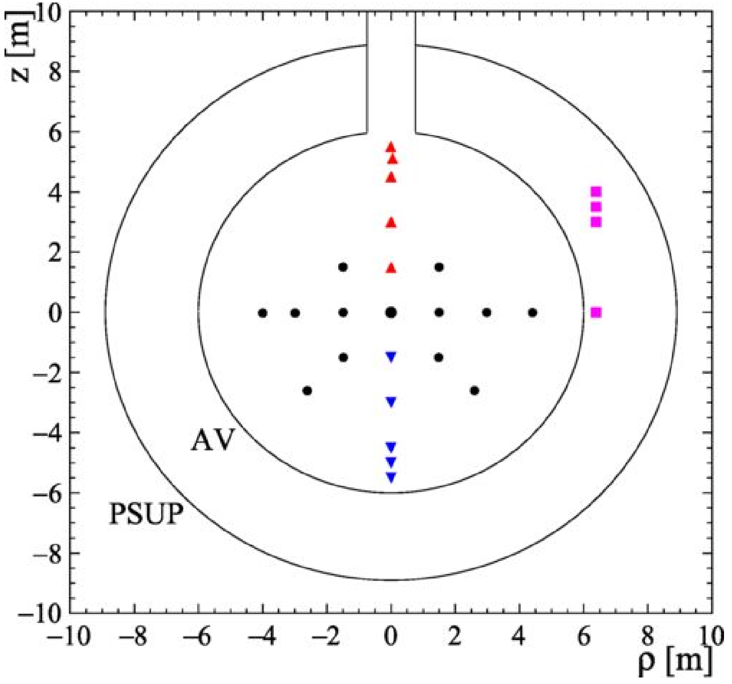
$$\frac{dN}{dt} = T \cdot R_p[PE \cdot (\lambda + R_d)\exp(-(\lambda + R_d)t) + (1 - PE) \cdot R_d \exp(-R_d t)]$$

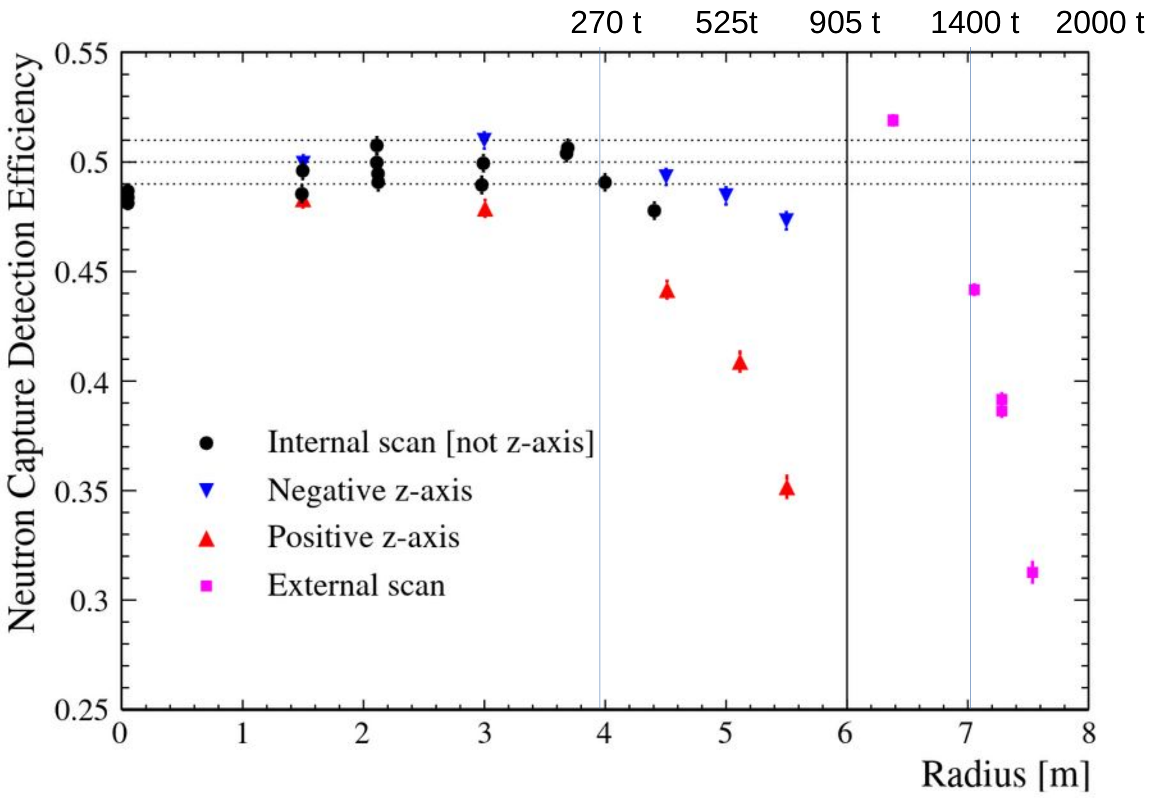
Measurement of neutron-proton capture in the SNO+ water phase Phys. Rev. C 102, 014002 (2020)

$$\sigma_{\mathrm{H},t} = 336.3^{+1.2}_{-1.5}\ \mathrm{mb}$$

Compatible to older measurements:
334.2±0.5 mb, Nucl. Phys. 74. 497 (1965)
332.6±0.7 mb, Phys. Rev. C 15, 1636 (1977)

highest efficiency in pure water





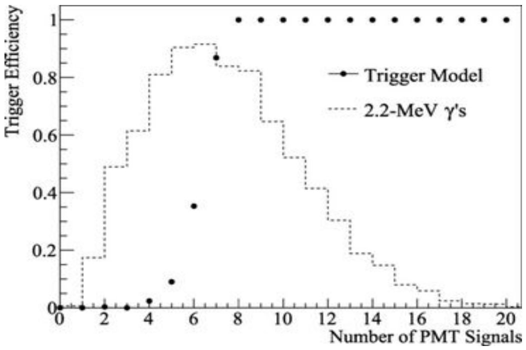
Phys. Rev. C 102, 014002 (2020)

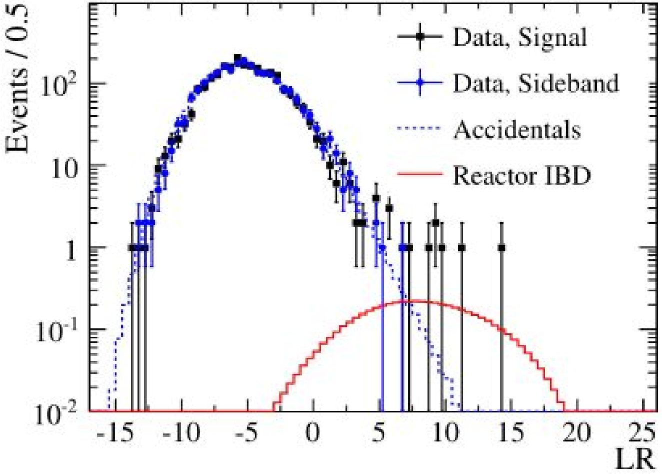
(49.08 ± 0.39)% efficiency for triggering on a neutron capture signal at detector center
extended fiducial mass for neutron capture based analyses including external water

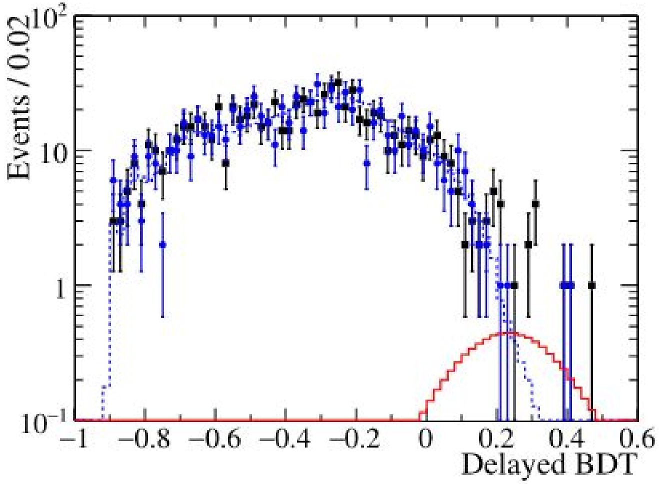
antineutrinos in pure water

neutron capture coincidence signal down from ~10 Hz (calibration) to ~10 nHz (reactors)

imagine a scaling up of the red lines if reactors were closer!



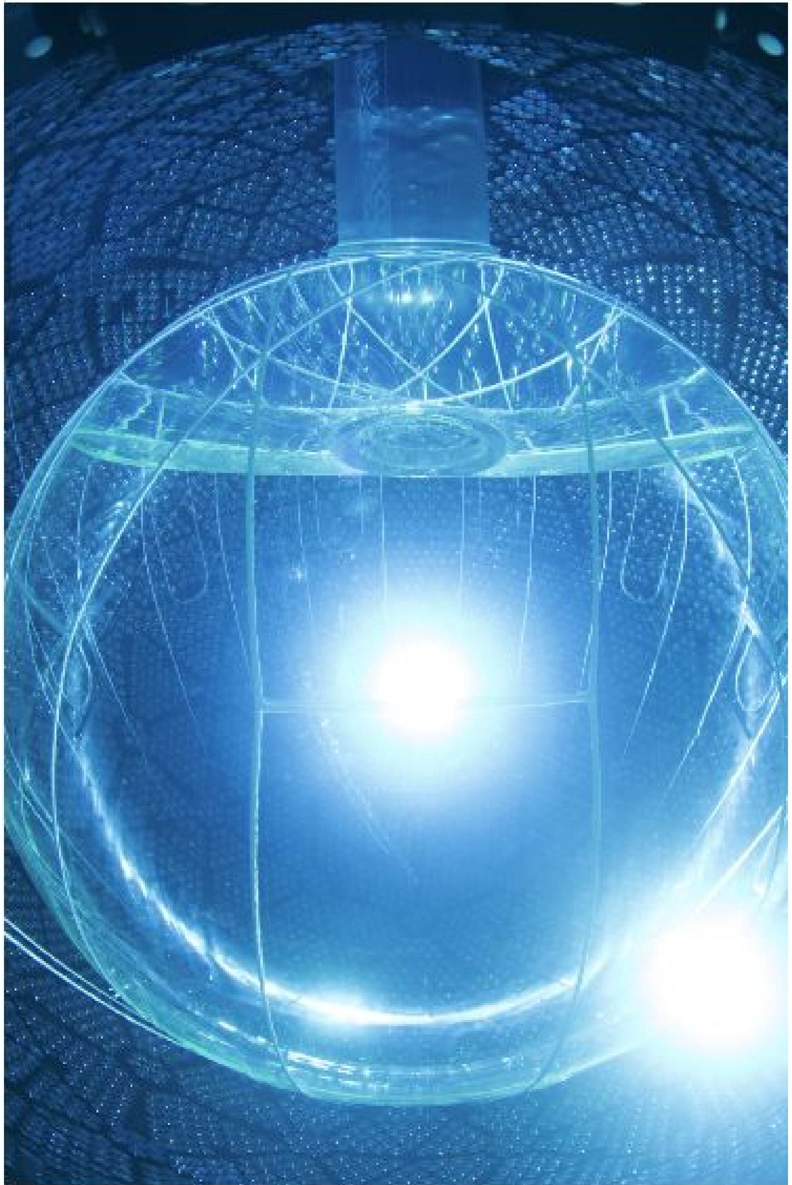




Main backgrounds:
accidental coincidences, C(α,n)O* interactions, atmospheric neutrinos...

Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+ Physical Review Letters (130) 091801, 2023

3.5 sigma observation, from 14 candidates (for 3.2 ± 1.0 bkg events expected)
seen by two independent blind analyses (each ~ 3.0 σ)

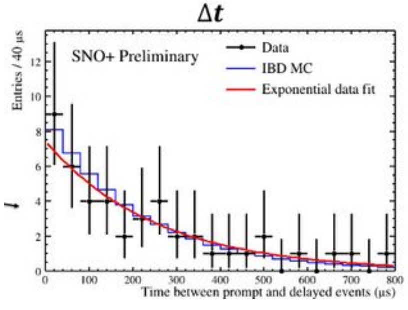


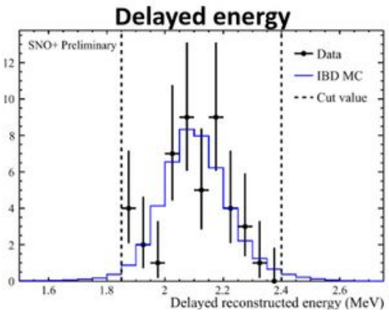
from water to scintillator

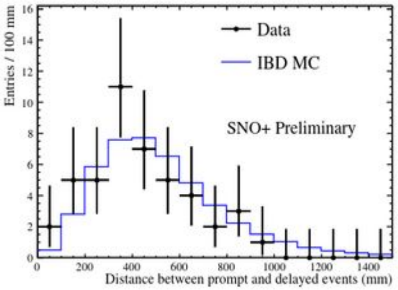
130 days with scintillator from the top down to the equator

scintillator higher light yield » much better energy resolution

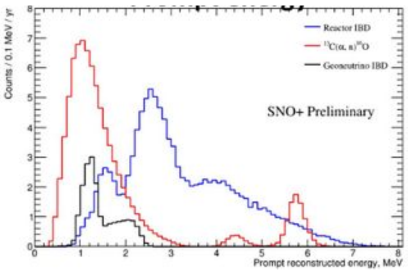
high purity scintillator » accidental coincidences negligible







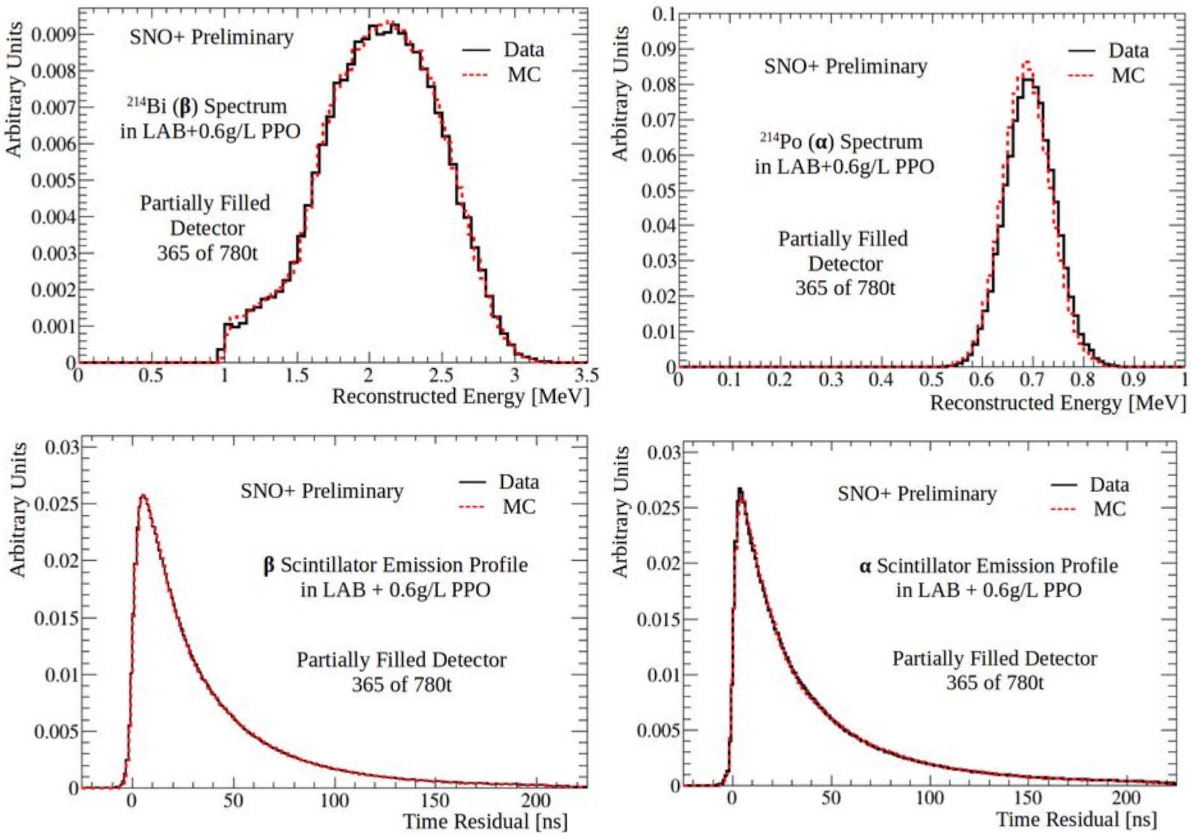
45 events seen for 44.9 expected



9.4 from reactor
2.2 from geoneutrinos
many from C(α,n)O background

Paper in preparation

calibration with backgrounds



Similar selection for Bi Po coincidences

- decaying rate, but high at start, excluded from subsequent IBD analysis

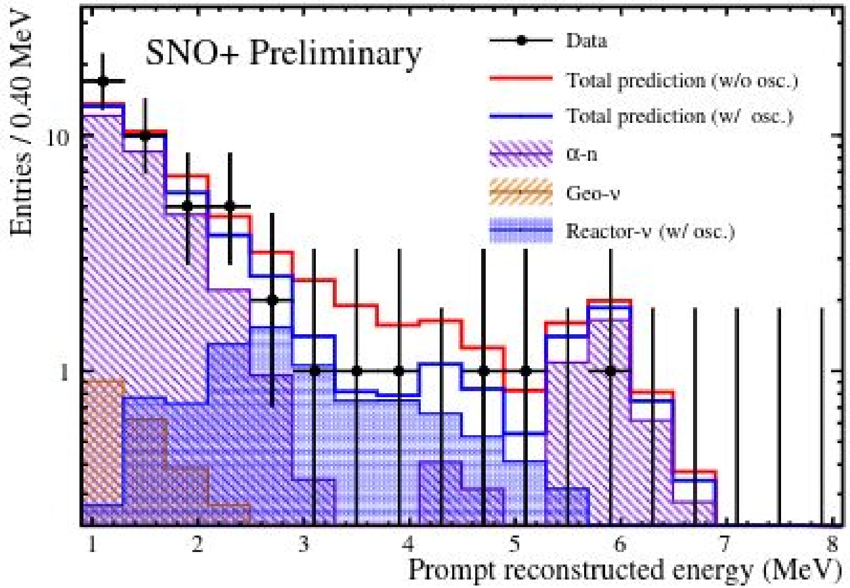
- measure light yield, Birks' constants, energy scale across active volume: **3% uncertainties in spectral fit**

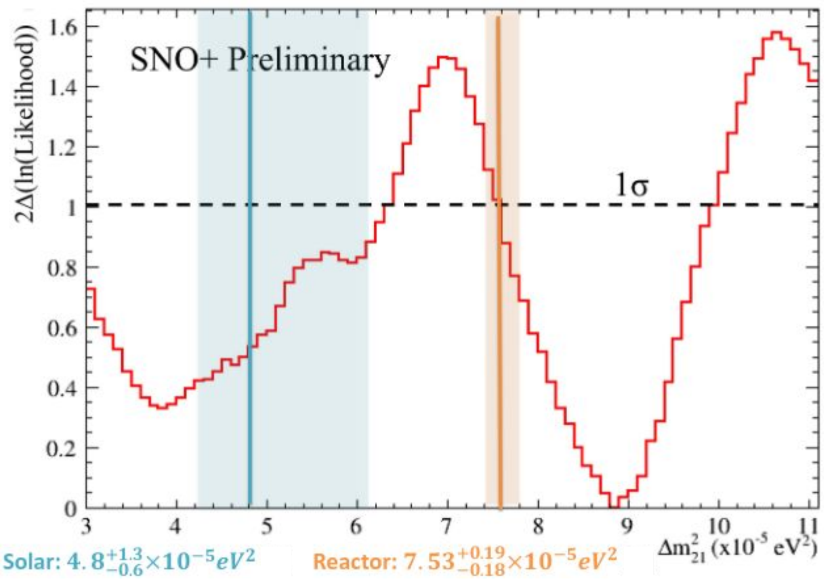
- measure scintillation emission times, essential for **Particle Identification**

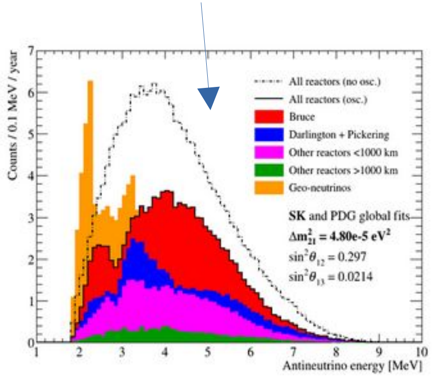
Monitoring of ^{210}Po, source of C(α,n)O

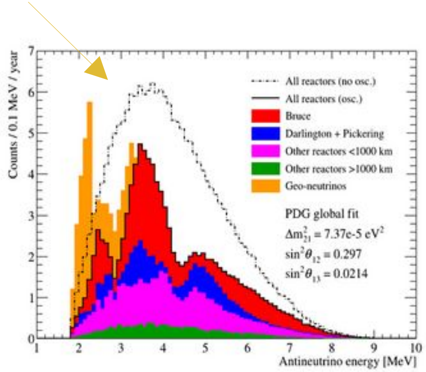
- constrained in the spectral fit w/ 30% uncertainty (100% for O* BR)

antineutrino spectral analysis







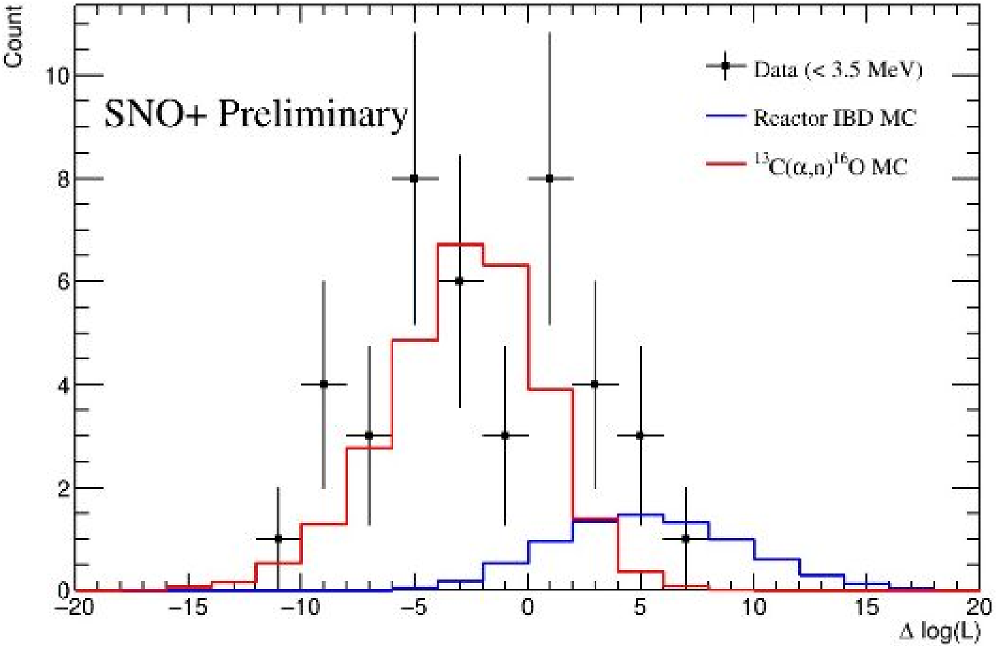


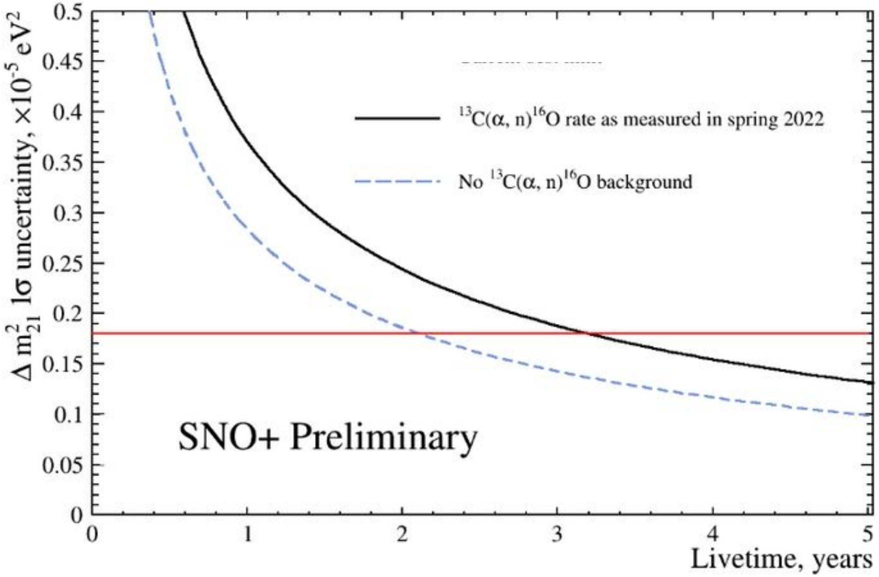
Data fully compatible with reactor spectra and normalization with oscillation parameters

geoneutrinos under (α,n) background

Paper in preparation

dealing with (α,n) backgrounds



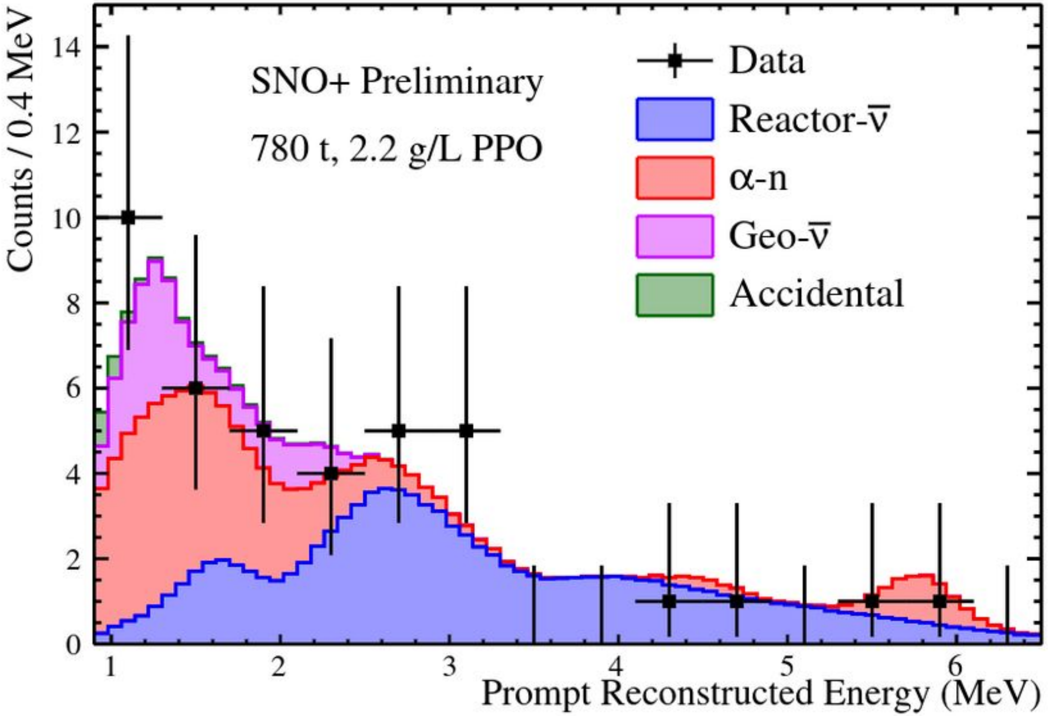


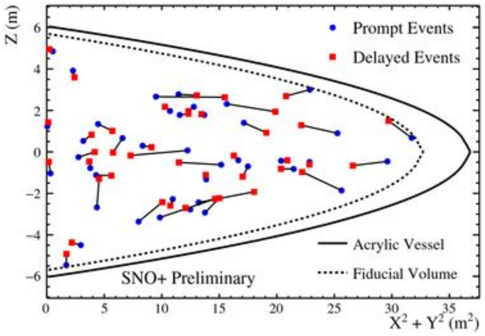
Use timing to identify proton scattered by neutrons, against IBD’s positron

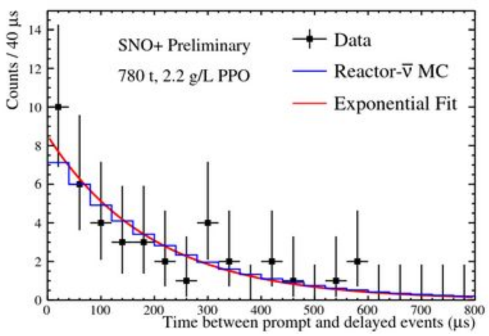
Will be re-checked and re-tuned for changing scintillator cocktail (PPO, bis-MSB)

No significant impact expected from Tellurium loading in the longest future phase

antineutrinos in full scintillator fill







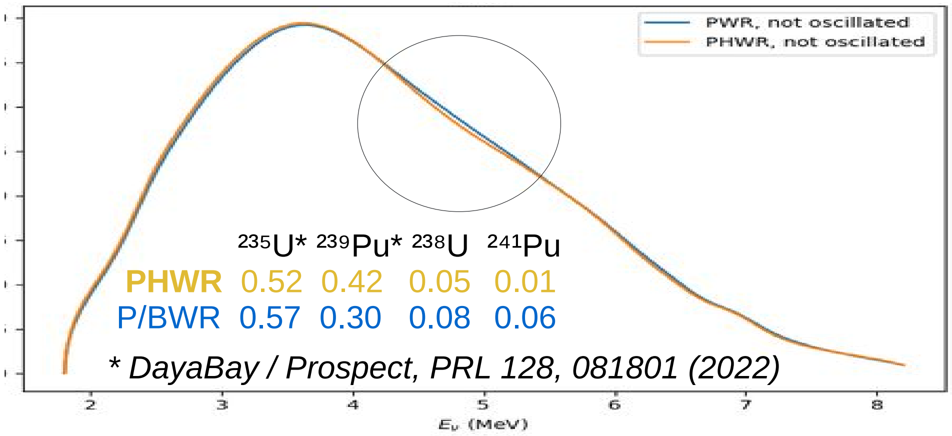
double volume and longer data-taking

with ~ 4.5 x reduction in (α,n)

geoneutrinos now visible!

Very preliminary, no fit attempted yet
- scintillator cocktail from 0.6 g/L to 2.2 g/L PPO
- non-final reconstruction, still updating calibration
- (α,n) identifier not yet applied, being re-tuned

antineutrino sources and fitting



	^{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

* *DayaBay / Prospect, PRL 128, 081801 (2022)*

Powers constrained for each reactor with monthly thermal power from IAEA (3% unc.) with hourly variations from IESO in Ontario

$P(L/E) = (1-\sin^2(0.25\, L/E\, \Delta m^2_{12}).\sin^2(2\theta_{12}))$
$.\cos^4\theta_{13}+\sin^4\theta_{13}$ (& even smaller matter-effect corr.)

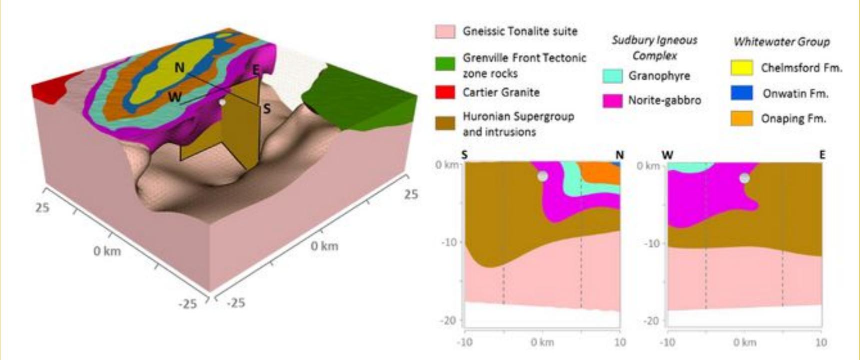
SNO+ is most sensitive to Δm^2_{12} from reactors (average out for geo-neutrinos at all distances)

Preliminary geoneutrino model:

dominated by local crust
working w/ geoscientists for characterization

Constrain flux and spectrum in oscillation fit

Then separate both components for geology



eg. Stratti et al, TAUP2020, doi:10.1088/1742-6596/1342/1/012020

antineutrinos in SNO+

First observation of reactor antineutrinos in a large Pure Water Cherenkov Detector

H_2O

SNO+ isolated a very small flux of antineutrinos from reactors at O(100 km)
proton-neutron captures seen with 50% efficiency in Pure Water volume

Confirmation of long base line antineutrino oscillation from CANDU reactors

SNO+ prepared to deal with significant amounts of the dominant (α,n) background

All components of antineutrino energy spectrum visible after full scintillator fill

LS

Sensitivity to Δm^2_{12} to be improved with larger statistics in the near future

Observation of geoneutrinos in a new geological setting (north american plate)

Will continue to measure antineutrinos throughout Tellurium phase

Te

Full potential will be achieved by adding all data together

Thank you!

LIP Coimbra
LIP Lisboa

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TRIUMF
University of Alberta
Queen's University
Laurentian University

TU Dresden

UNAM

Boston University
BNL
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