The
SNO+ Experiment
Reactor & Solar ν Prospects

Benjamin Tam (for the SNO+ Collaboration)
Neutrino Oscillation Workshop
9 September 2022

Main detector body is 6m radius acrylic vessel

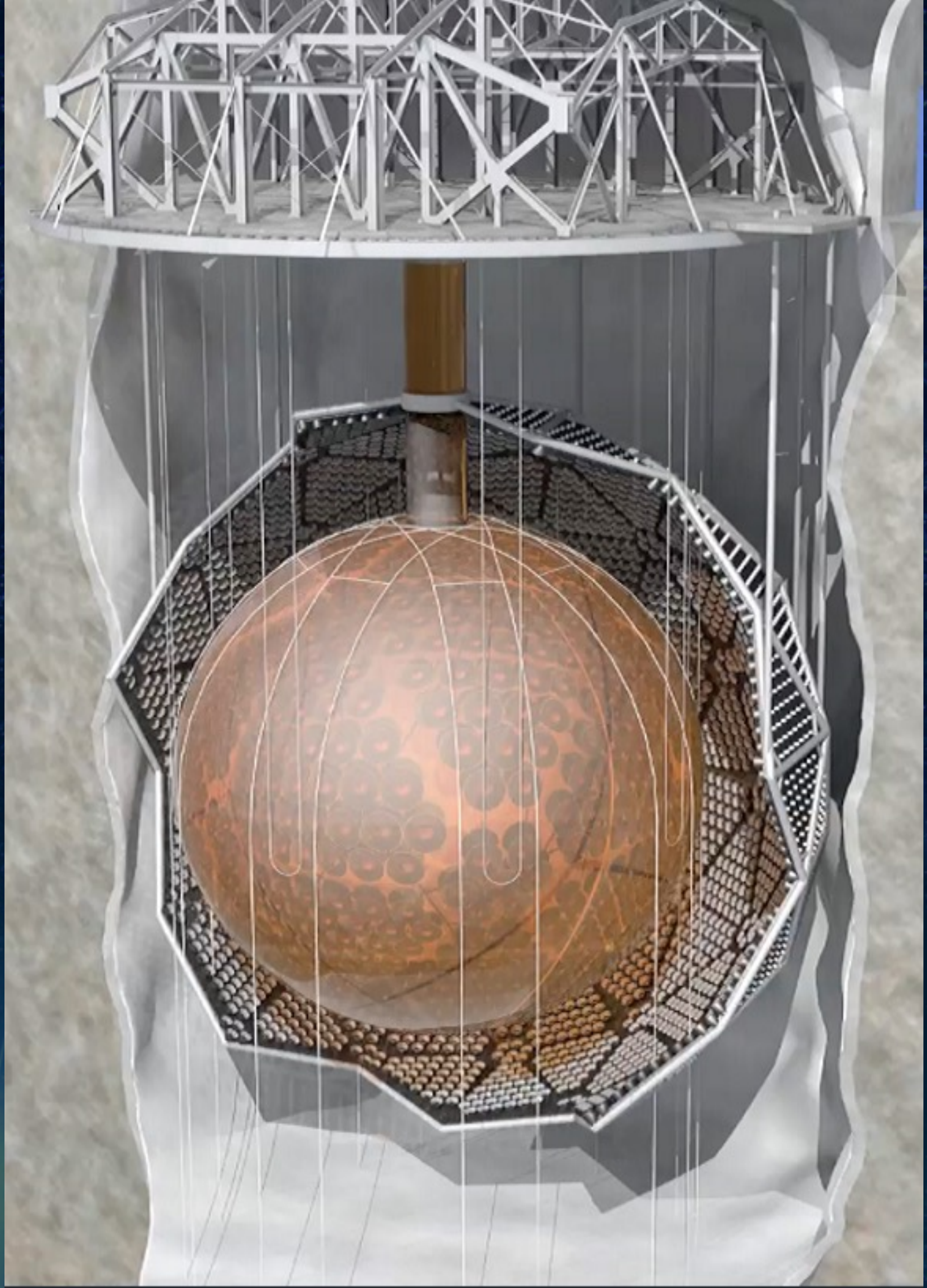
905 m^3 detector medium volume

2070 m rock overburden
6010 m.w.e. ($0.286 \pm 0.009\ \mu/m^2/d$)

7000 m^3 external ultrapure water shielding

N_2 Cover Gas blanket across entire detector

Capability to quickly recirculate media and shielding through purpose-built purification plants



System of low-radioactivity external ropes to account for buoyancy differences between various media

External 8.9m radius steel PMT support structure with built-in LED/laser calibration system

9800 8” PMTs with 27-cm diameter concentrators (54% effective photocoverage)

Rope-based calibration system for internal and external source deployments

Upgraded DAQ and electronics hardware

Detector Hardware: JINST 16 P08059

University of Alberta
U.C. Berkeley
LBNL
Boston University
Brookhaven
University of Chicago
U.C. Davis
T.U. Dresden
Lancaster University
Laurentian University
LIP Lisbon
LIP Coimbra
Kings College London

University of Liverpool
UNAM
University of Oxford
University of Pennsylvania
Queen's University
Queen Mary University
SNOLAB
Shandong University
University of Sussex
TRIUMF

Three Operational Phases based on AV medium

Water Phase

May 2017 - July 2019

905 tonnes ultrapure Water

- Invisible Nucleon Decay
- Solar neutrinos
- Reactor anti-neutrinos
- Supernova neutrinos

Scintillator Fill

Scintillator Phase

Started April 2022

780 tonnes liquid scintillator

- Solar neutrinos
- Reactor anti-neutrinos
- Geo-neutrinos
- Supernova neutrinos
- Light DM & MIMP DM
- Axion-like particles

Te Loading

Tellurium Phase

Deployment 2024

780 tonnes liquid scintillator doped with >4 tonnes ^{nat}Te

- Scintillator Phase Physics Programme
- Neutrinoless double beta decay in ^{130}Te

Three Operational Phases based on AV medium

Water Phase

May 2017 - July 2019

905 tonnes ultrapure Water

- Invisible Nucleon Decay
- Solar neutrinos
- Reactor anti-neutrinos
- Supernova neutrinos

Scintillator Fill

Scintillator Phase

Started April 2022

780 tonnes liquid scintillator

- Solar neutrinos
- Reactor anti-neutrinos
- Geo-neutrinos
- Supernova neutrinos
- Light DM & MIMP DM
- Axion-like particles

Te Loading

Tellurium Phase

Deployment 2024

780 tonnes liquid scintillator doped with >4 tonnes ^{nat}Te

- Scintillator Phase Physics Programme
- Neutrinoless double beta decay in ^{130}Te

Bonus!

Partial Fill

March – October 2020
365 tonnes liquid scintillator

Three Operational Phases based on AV medium

Water Phase

May 2017 - July 2019

905 tonnes ultrapure Water

- Invisible Nucleon Decay
- Solar neutrinos
- Reactor anti-neutrinos
- Supernova neutrinos

→ Scintillator Fill →

Scintillator Phase

Started April 2022

780 tonnes liquid scintillator

- Solar neutrinos
- Reactor anti-neutrinos
- Geo-neutrinos
- Supernova neutrinos
- Light DM & MIMP DM
- Axion-like particles

→ Te Loading →

Tellurium Phase

Deployment 2024

780 tonnes liquid scintillator doped with >4 tonnes ^{nat}Te

- Scintillator Phase Physics Programme
- Neutrinoless double beta decay in ^{130}Te

Bonus!

Partial Fill

March – October 2020
365 tonnes liquid scintillator

Water Phase – Invisible Nucleon Decay

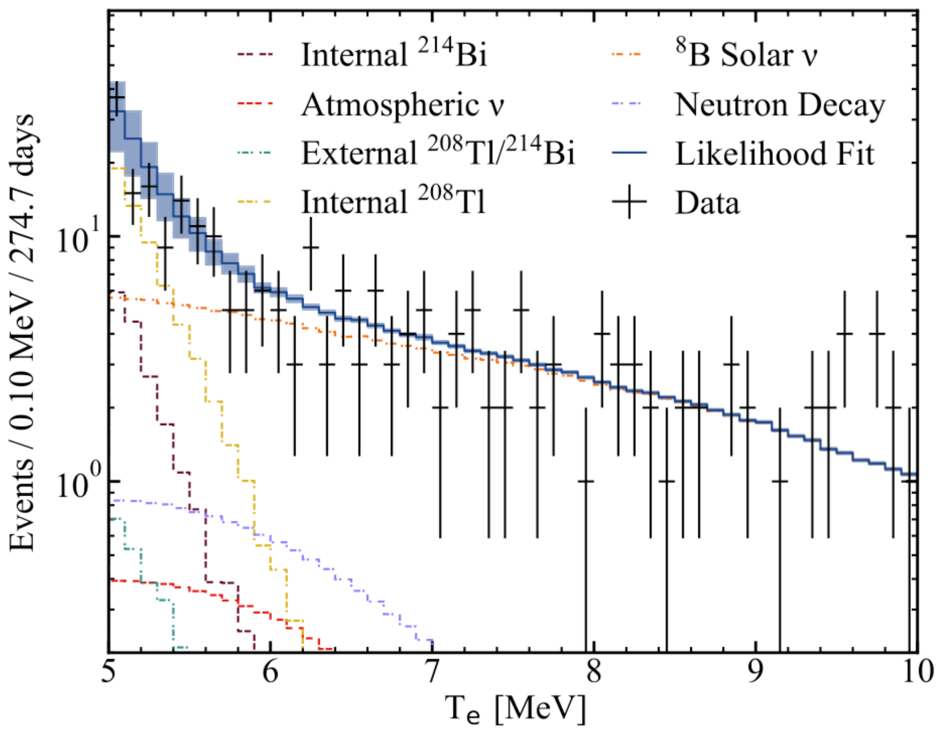
- Nucleon decay modes to final states where no visible energy is deposited

  Following modes investigated (previous best limits):
  - *n* → inv (KamLAND)
  - *p* → inv (SNO)
  - *pp* → inv (Borexino CTF)
  - *pn* → inv (Radiochemical)
  - *nn* → inv (KamLAND)

- First search performed using initial commissioning data

  Phys.Rev.D 99, 032008
- Improved search performed using fully commissioned detector

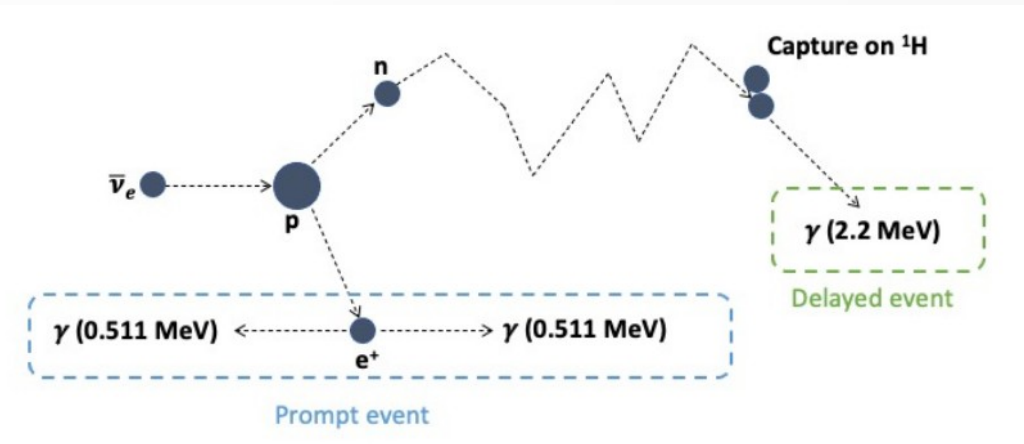
  Phys.Rev.D 105, 112012
- New world-leading limits on *n*, *p*, *pp*, *np* modes



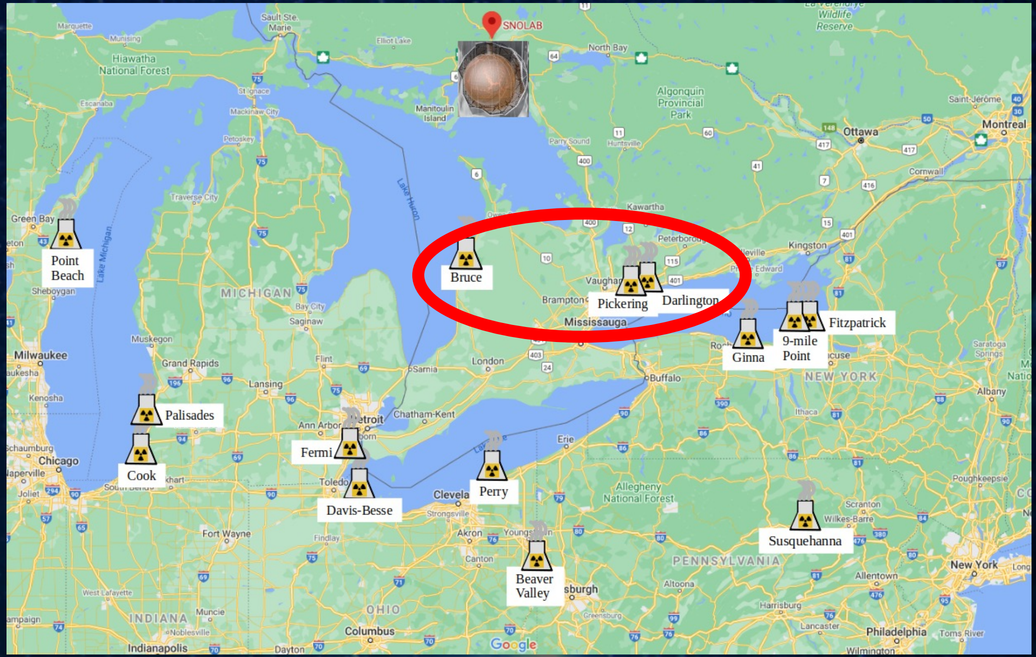
Decay mode	Partial lifetime limit	Existing limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

Water Phase – Reactor Antineutrinos

Detection of reactor antineutrinos through inverse beta decay



- 60% of IBD events occur from 3 reactors (18 cores) 240km, 340km, 350km away
- Excellent L/E for sensitivity to Δm^2_{21}
- Neutron-Proton capture cross-section and timing measured, 50% detection efficiency
  Phys.Rev.C 102, 014002
- First measurement of reactor antineutrinos using pure water with >3σ detection significance



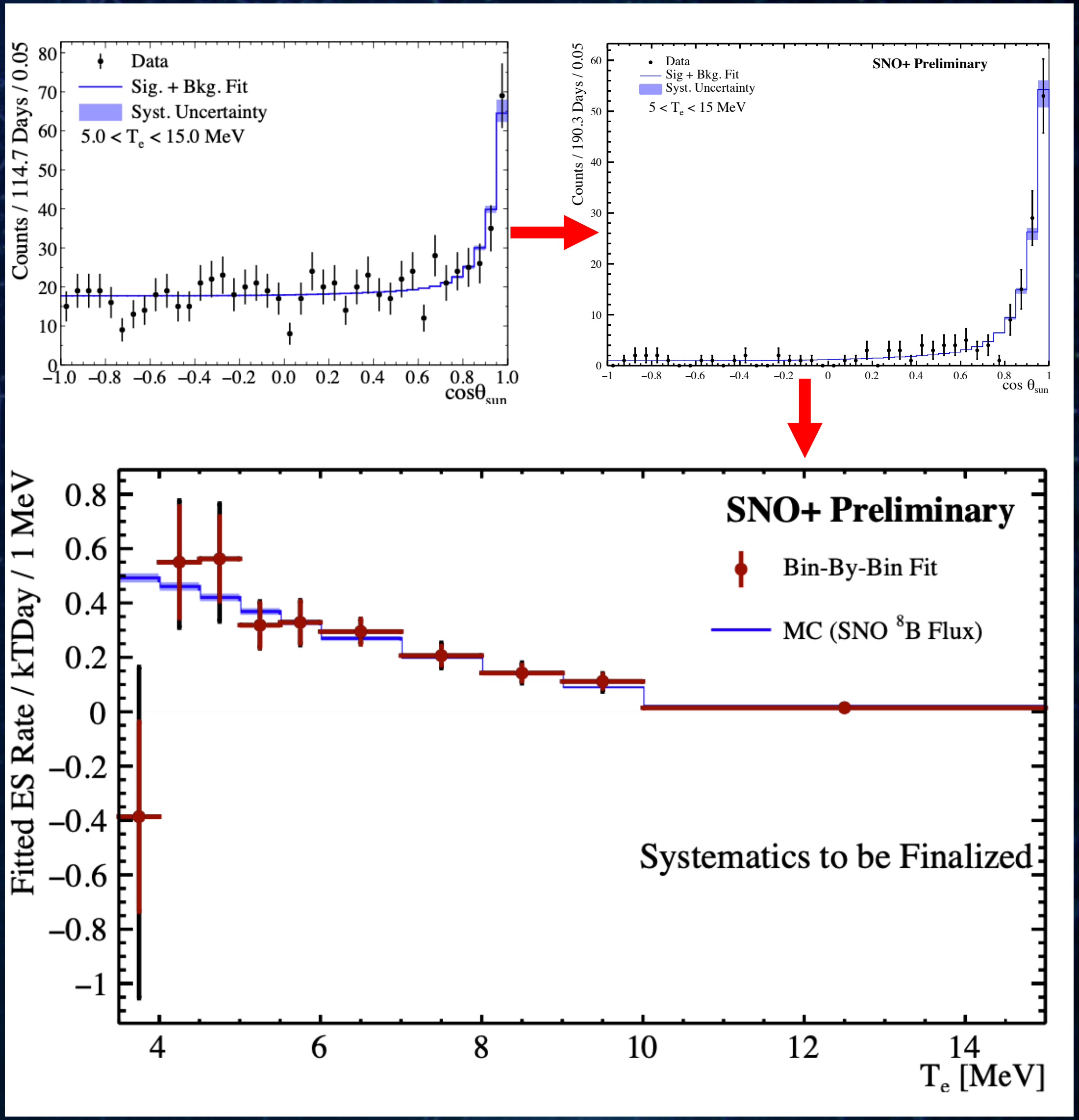
Water Phase – Solar Neutrinos

- ^{8}B Solar Neutrino flux measured with initial commissioning data
  Phys.Rev.D 99, 012012

$$\Phi_{8_B} = 5.95^{+0.75}_{-0.71}(\text{stat.})^{+0.28}_{-0.30}(\text{syst.}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

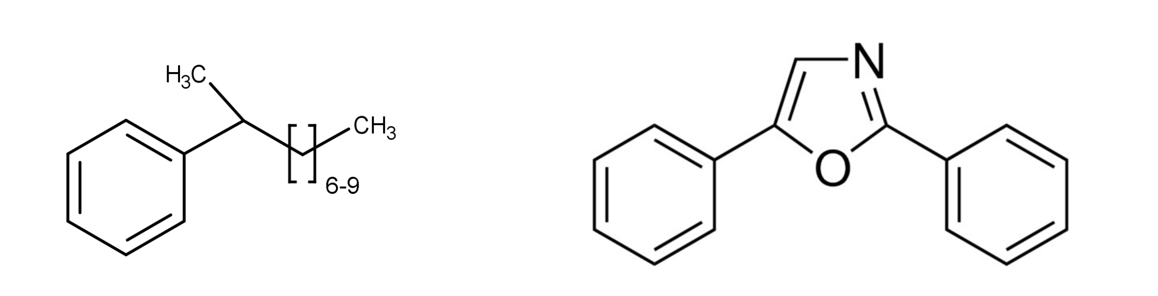
  - Uses directionality of electron recoil relative to the position of the sun, $\cos\theta_{sun}$
  - Low background levels dominated by ^{222}Rn
  - Consistent with SK, SNO

- Analysis on new data set complete
  - New data set uses fully commissioned detector
  - N_2 cover gas to suppress Rn backgrounds



Liquid Scintillator

- Linear Alkylbenzene (LAB) + 2.2g/L Diphenyloxazole (PPO)



- Developed by SNO+, successfully used in Daya Bay, RENO, and others
- LAB more compatible with acrylic and safer than other widespread liquid scintillators

  Pseudocumene (PC) (Borexino, KamLAND)

  Phenyl-o-xylylethane (PXE) (Double CHOOZ)
- PPO acts as a fluor emitting in the ~390nm range
- >50x higher light yield than water

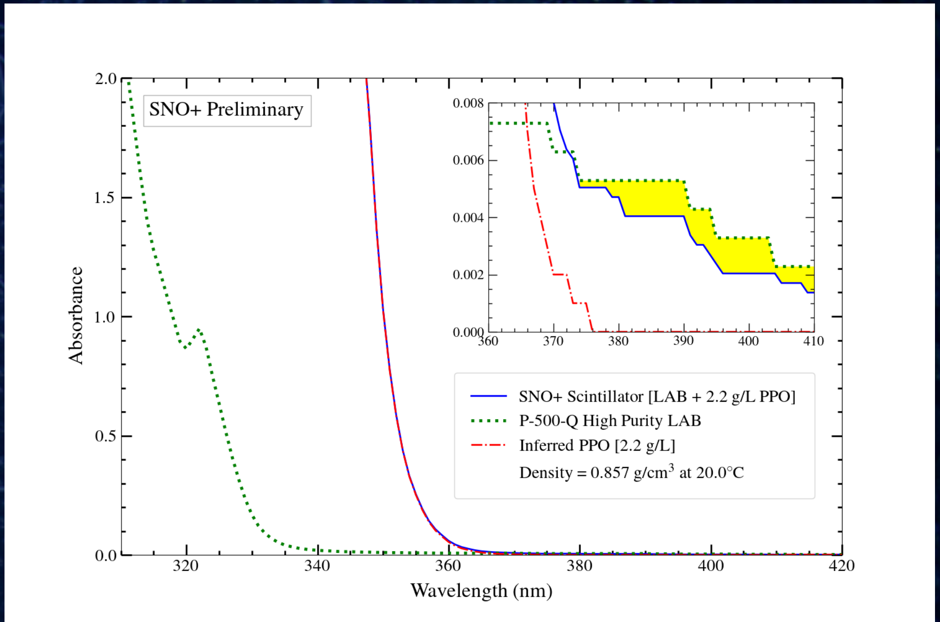
SNO+ Scintillator: JINST 16 P05009

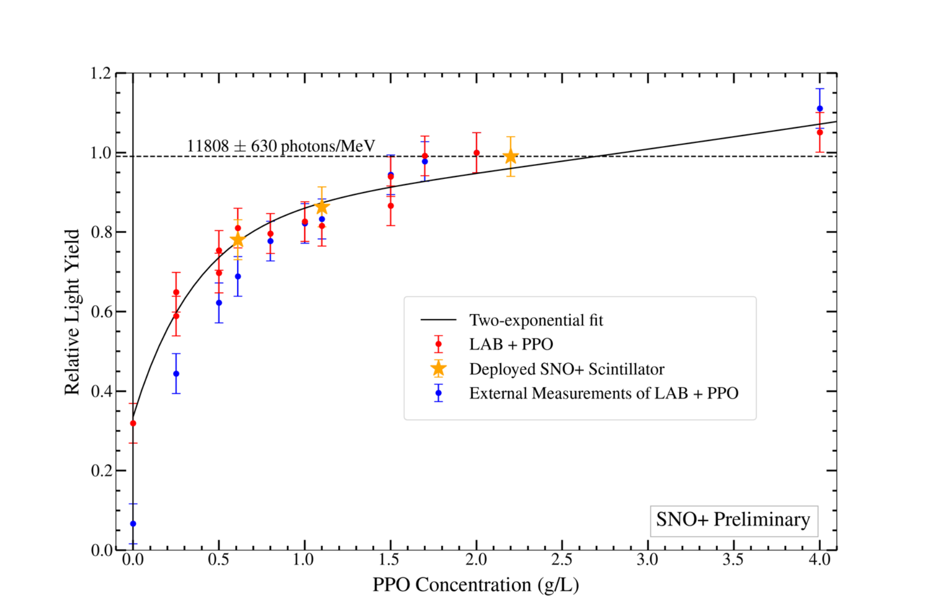
Scintillator Fill

- LAB + PPO purified and deployed using purpose-build purification plant

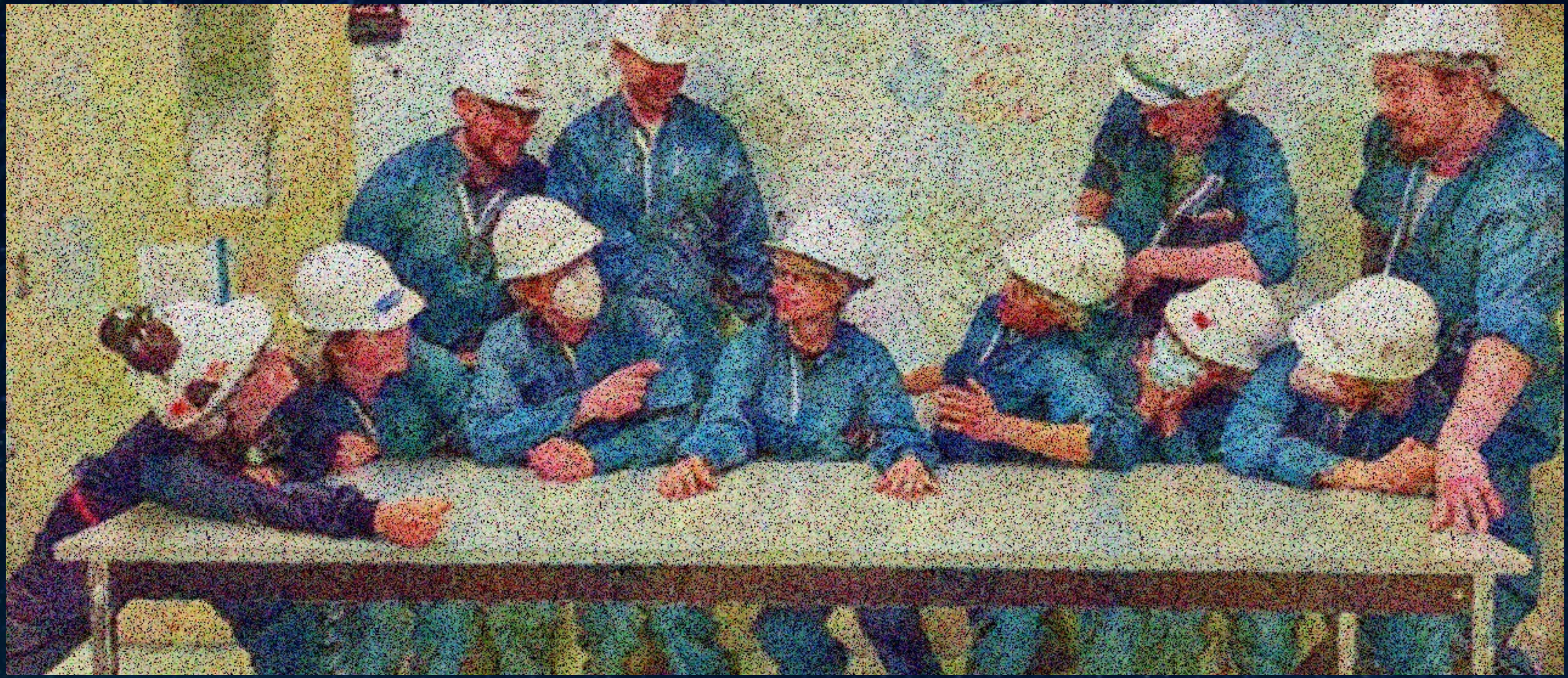
  Purified through:
  - Multi-stage distillation
  - N_2 stripping
  - Water extractions
- Started July 2019
- Paused for 8 months at 365 tonnes LAB + 0.6 g/L PPO

  (COVID-19 access restrictions)
- Ultra-purity of scintillator verified through extensive suite of hourly measurements during filling





Scintillator Phase Started April 29th, 2022

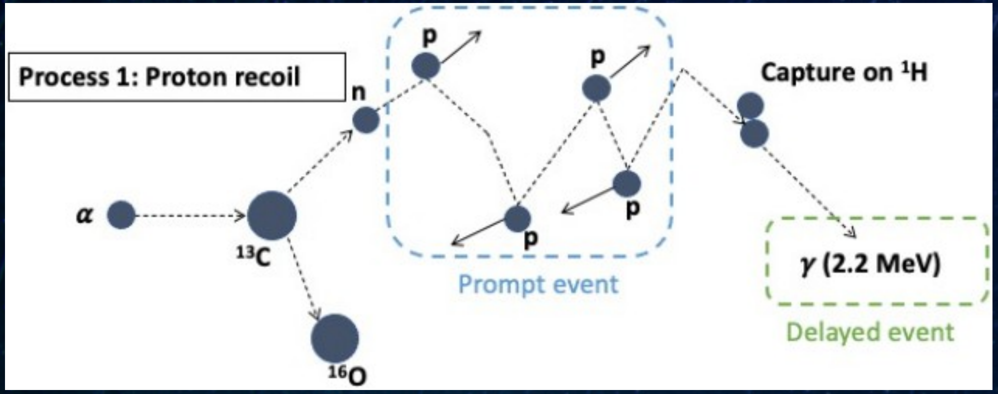


"The Last Sample"

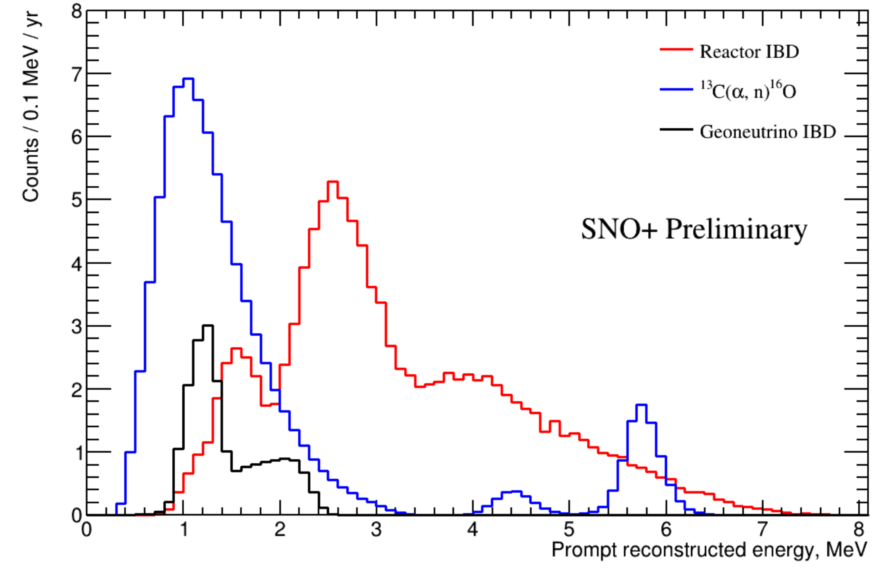
Final deployment of
780 tonnes LAB + 2.2 g/L PPO

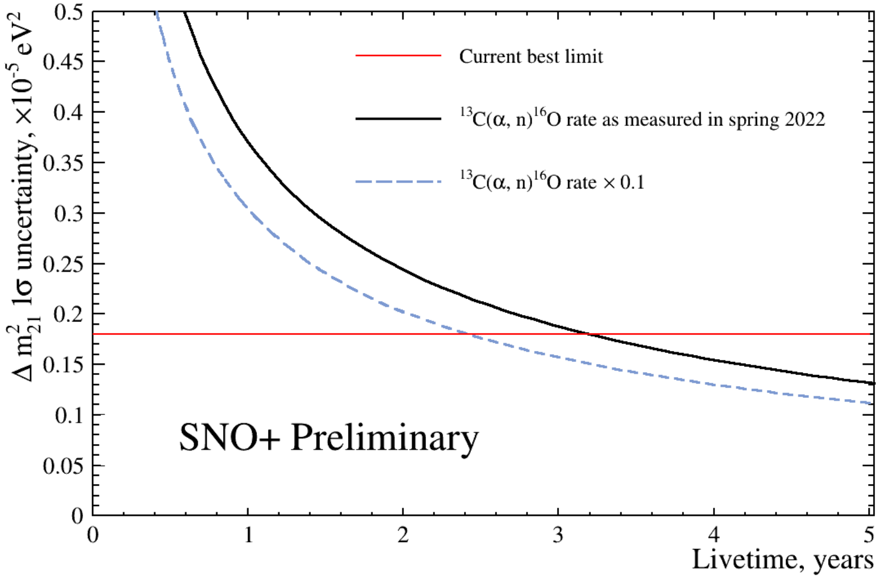
Scintillator Phase - Reactor Antineutrinos

- Measurement of reactor antineutrinos underway
- Dominant background are $^{13}C(\alpha,n)^{16}O$ events caused by ^{210}Po decays within the detector



- New pulse shape discriminator to separate IBD and (α,n) events, rejecting backgrounds by a factor of 10
- Achieved by utilising slower timing profile of proton recoils from (α,n) events



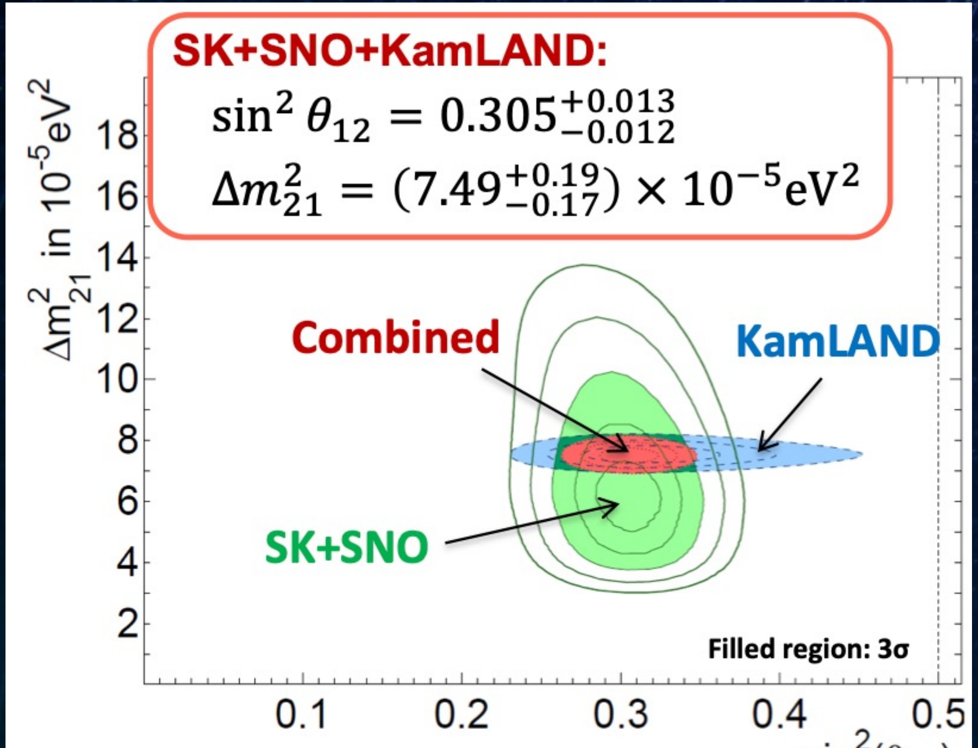


Scintillator Phase - Reactor Antineutrinos

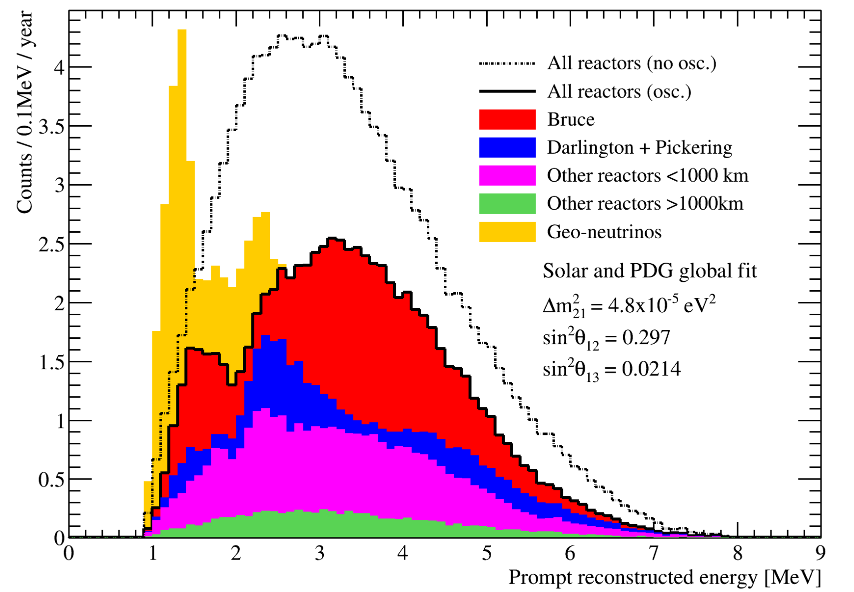
Will inform current 1.5σ tension between SNO/Super-K and KamLAND measurements

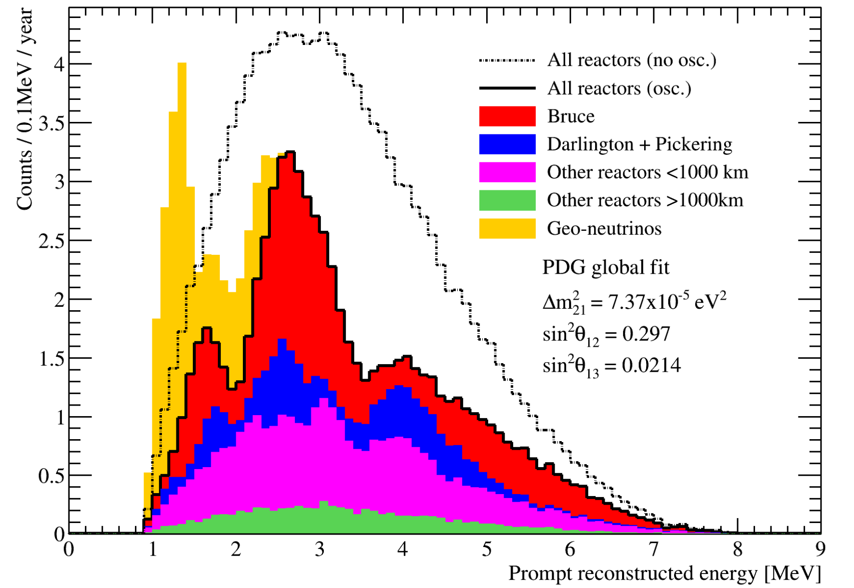
SK+SNO: $\Delta m^2_{21} = 5.1^{+1.3}_{-1.0} \times 10^{-5}\ \mathrm{eV}^2$

KamLAND: $\Delta m^2_{21} = 7.50^{+0.20}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$



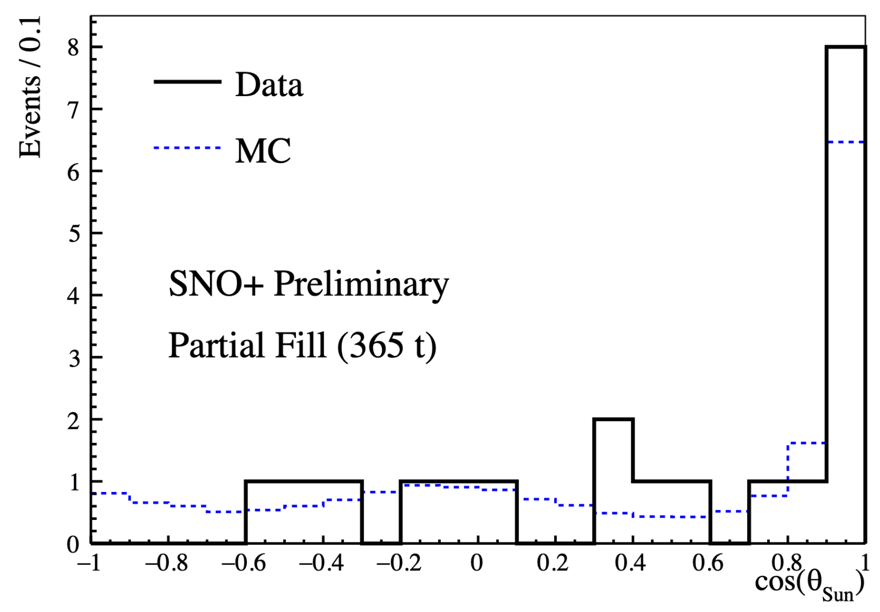
Y. Takeuchi (SK Collaboration) NOW22

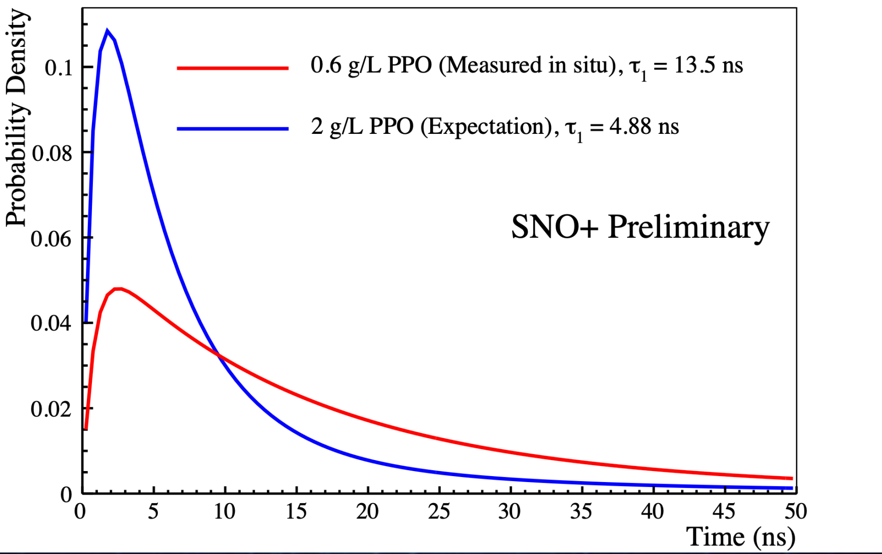




Scintillator Phase - Direction Reconstruction

- Isotropic scintillation light makes directionality traditionally challenging to determine
- New event-by-event direction reconstruction technique developed – first in liquid scintillation experiment
- Determined by fitting prompt timing profiles to combined Cherenkov-scintillation 2D PDFs
- Demonstrated using partial fill data (0.6 g/L)
- Also possible with nominal PPO concentration (2.2 g/L)
- Will enhance solar neutrino analyses in the scintillator phase





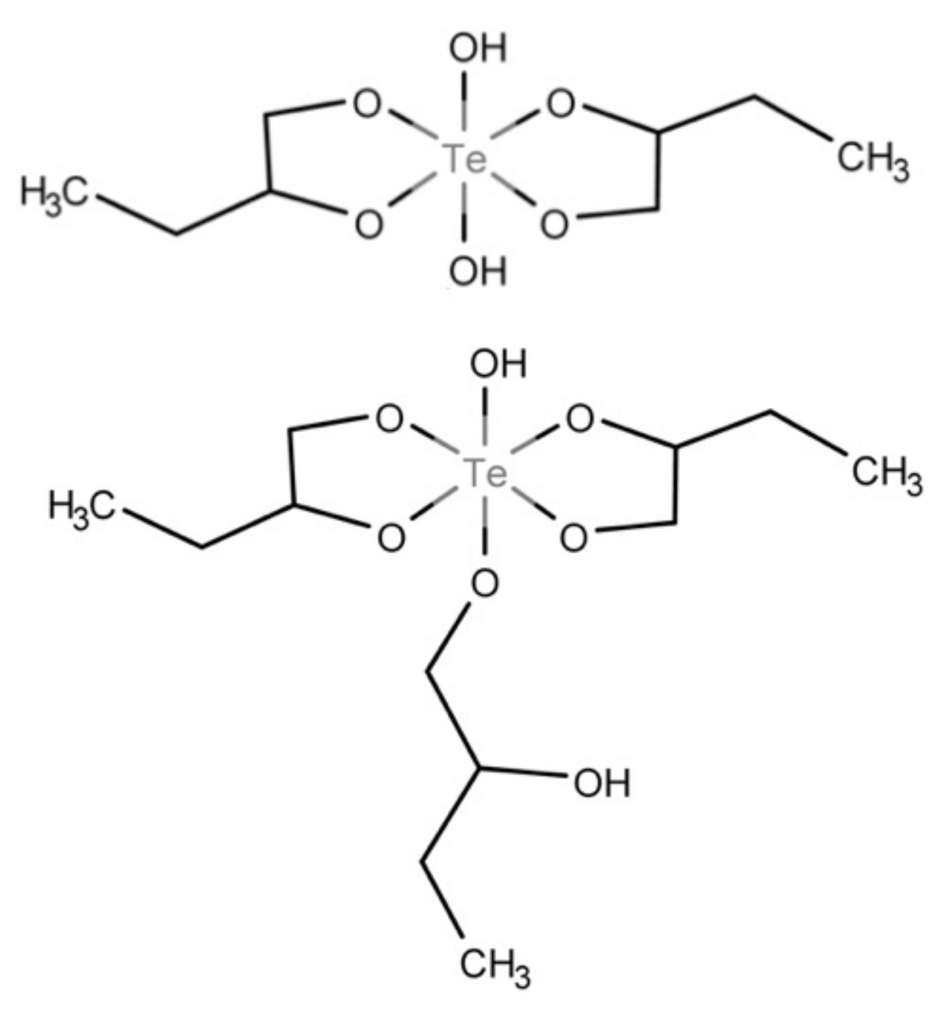
Tellurium Loading

- Main SNO+ goal: searching for $0\nu\beta\beta$ in ^{130}Te
- Novel metal-loading technique to dope SNO+ LS with Te
  - Achieved by diolising telluric acid (TeA), forming Tellurium Butanediol (TeBD) that readily dissolves in LAB
  - Additives introduced to scintillator to further boost stability and light yield
    - N,n-dimethyldodecylamine (DDA)
    - 1,4-Bis(2-methylstyryl)benzene (Bis-MSB)

Planned Cocktail Composition:

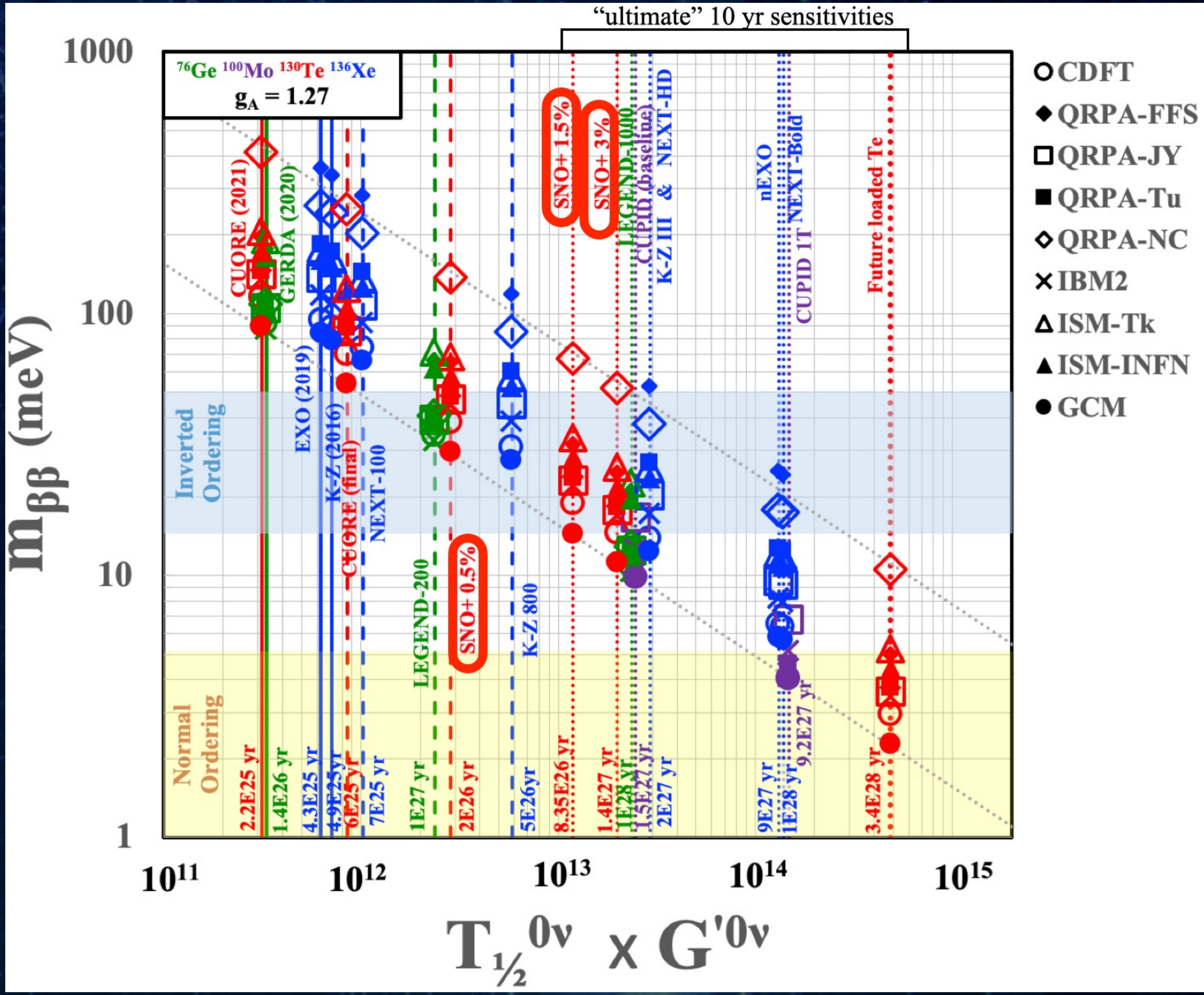
LAB + 2.2 g/L PPO + 5 mg/L bisMSB

+ TeBD + DDA (0.5 molar ratio DDA:Te)



Tellurium Phase - 0νββ

- Tellurium will be purified and deployed using 2 additional purification plants underground
  - Plant construction completed, commissioning in final stages
  - TeA stored underground since 2015 to minimise cosmogenic backgrounds
- Initial loading of 0.5% ^{nat}Te
  - ^{130}Te has a natural abundance of 34%
- Sensitive to $T^{0\nu}_{1/2} = 2 \times 10^{26}$ yr after 3 years data taking
- Further loading planned and possible
- May probe below inverted ordering parameter space
- Initial deployment planned 2024

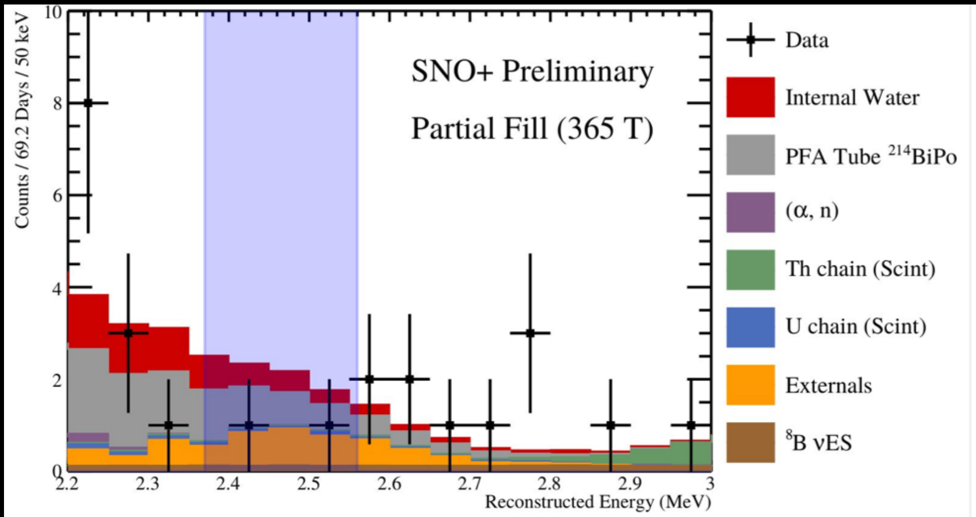


SNO+ scintillator phase well underway!

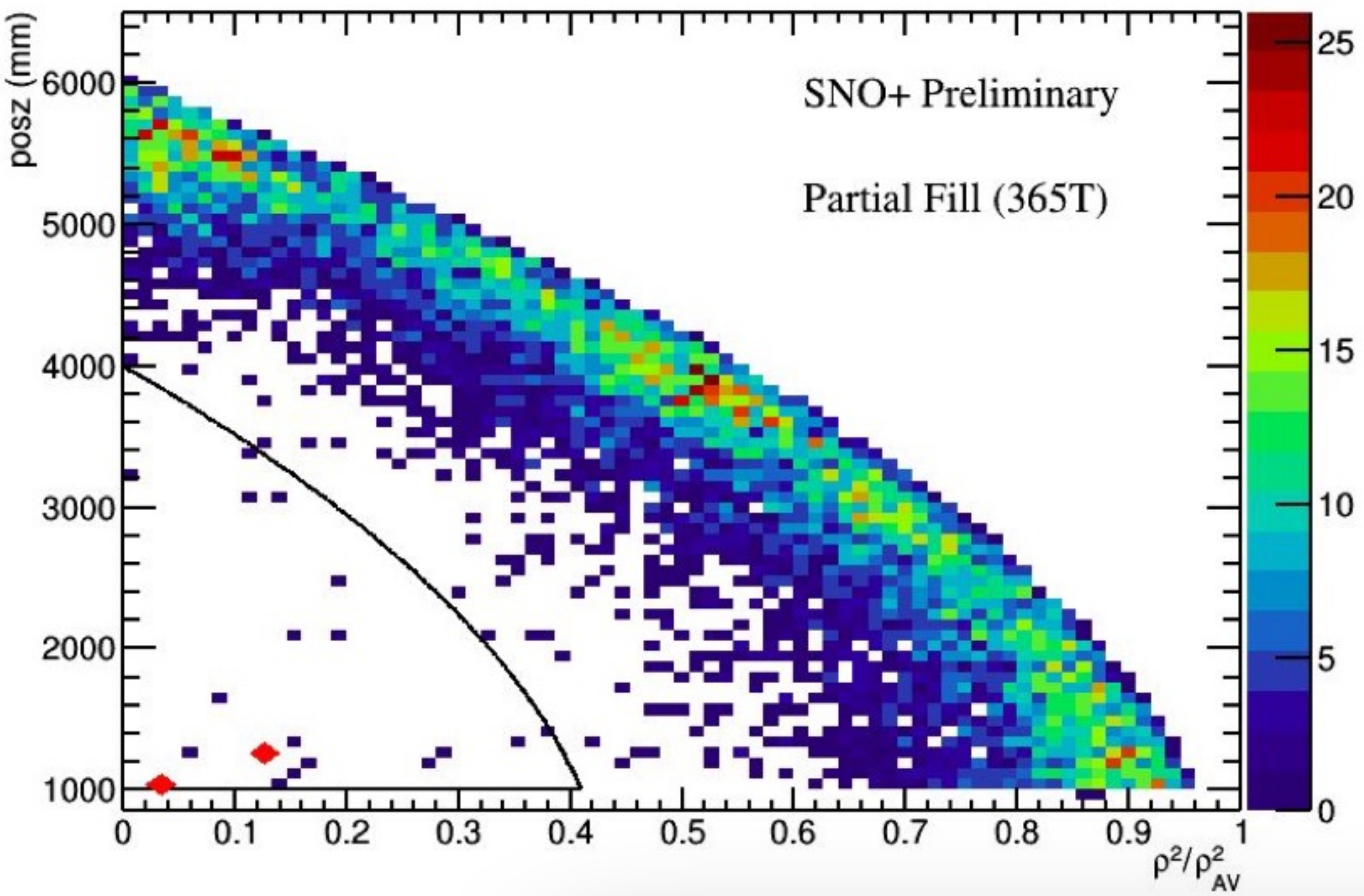
New physics results coming imminently…

Backups

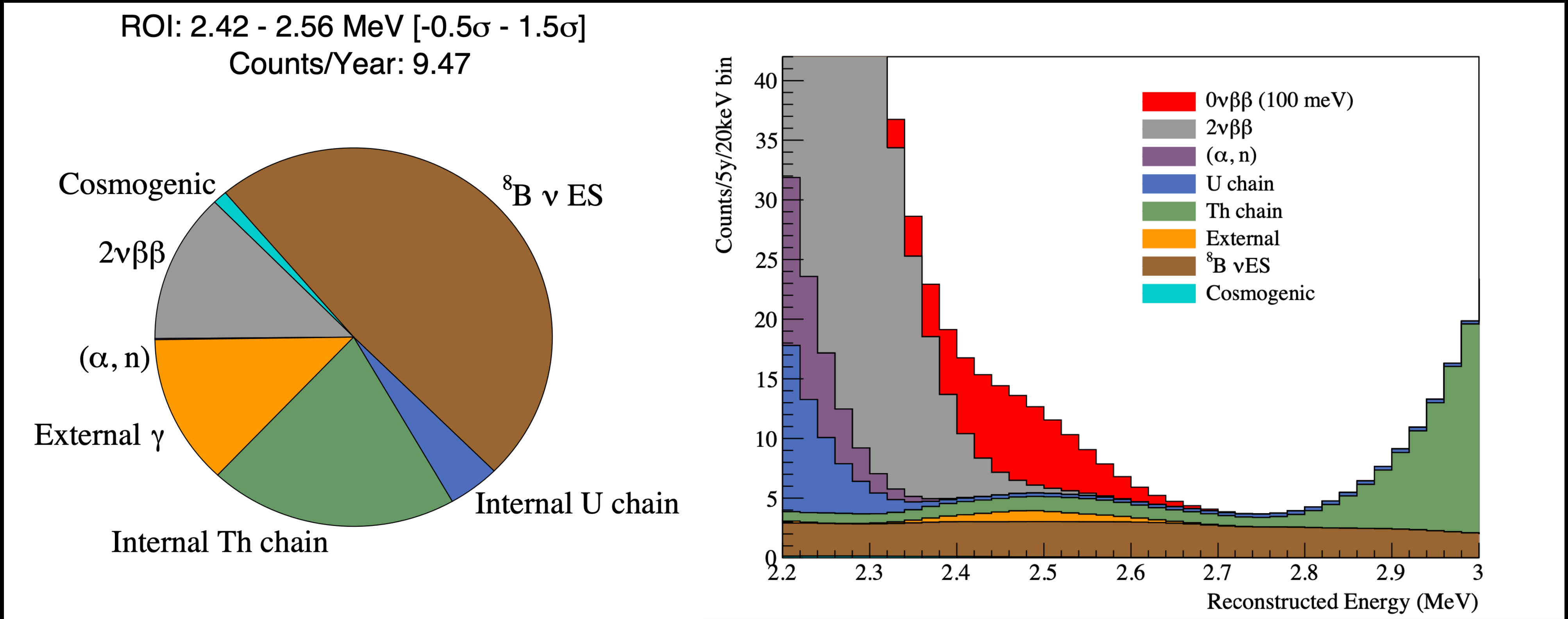
Backgrounds (Partial Fill)



Background	Expected Counts in Partial Fill ROI
Internal Water	1.8
PFA Tube ^{214}BiPo	2.9
Externals	2.5
(α, n)	0
Th Chain (Scint)	0.1
U Chain (Scint)	0.3
^{8}B νES	0.5
Total Backgrounds	8.0



Backgrounds (Projected Te Phase)



Improved Nucleon Decay Statistics

TABLE I. Optimized fiducial volume and livetime for each of the included datasets.

Observable	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
R (m) max	5.1	5.1	5.1	5.1	5.4	5.2
Z (m) [min, max]	[−6.0, 1.5]	[−6.0, 1.5]	[−6.0, 1.5]	[−3.1, 1.9]	[−6.0, 2.0]	[−6.0, 3.0]
Livetime (days)	5.0	14.6	30.2	28.9	11.2	184.8

	Signal efficiency (%)				
Data set	n	p	pp	np	nn
1	$11.4^{+0.7}_{-0.7}$	$13.2^{+0.7}_{-0.7}$	$11.5^{+0.5}_{-0.5}$	$6.6^{+0.3}_{-0.3}$	$1.84^{+0.07}_{-0.06}$
2	$11.6^{+0.7}_{-0.7}$	$13.3^{+0.7}_{-0.7}$	$11.5^{+0.5}_{-0.5}$	$6.6^{+0.3}_{-0.3}$	$1.84^{+0.07}_{-0.06}$
3	$11.5^{+0.7}_{-0.7}$	$13.3^{+0.7}_{-0.7}$	$11.5^{+0.5}_{-0.5}$	$6.6^{+0.3}_{-0.3}$	$1.84^{+0.07}_{-0.06}$
4	$10.9^{+0.7}_{-0.6}$	$12.6^{+0.6}_{-0.6}$	$10.8^{+0.5}_{-0.5}$	$6.2^{+0.3}_{-0.3}$	$1.72^{+0.07}_{-0.05}$
5	$14.6^{+0.9}_{-0.8}$	$16.8^{+0.8}_{-0.8}$	$14.4^{+0.6}_{-0.6}$	$8.3^{+0.4}_{-0.4}$	$2.31^{+0.09}_{-0.07}$
6	$13.9^{+0.4}_{-0.4}$	$16.4^{+0.4}_{-0.4}$	$14.2^{+0.3}_{-0.3}$	$8.2^{+0.2}_{-0.2}$	$2.38^{+0.04}_{-0.02}$

TABLE II. Summary of the evaluated systematic uncertainties for the reconstructed parameters, for the various datasets. Due to updates in the optical modeling, the final dataset (6) has a separate evaluation of these uncertainties from the previous datasets (1–5) [6].

Parameter	Uncertainty (1–5)	Uncertainty (6)
x offset (mm)	$^{+16.4}_{-18.2}$	$^{+50.1}_{-55.6}$
y offset (mm)	$^{+22.3}_{-19.2}$	$^{+47.7}_{-59.6}$
z offset (mm)	$^{+38.4}_{-16.7}$	$^{+75.8}_{-34.7}$
x scale (%)	$^{+0.91}_{-1.01}$	$(x>0)^{+0.16}_{-0.23}$ $(x<0)^{+0.17}_{-0.30}$
y scale (%)	$^{+0.92}_{-1.02}$	$(y>0)^{+0.12}_{-0.22}$ $(y<0)^{+0.17}_{-0.45}$
z scale (%)	$^{+0.91}_{-0.99}$	$(z>0)^{+0.30}_{-0.42}$ $(z<0)^{+0.09}_{-0.24}$
x resolution (mm)	104	$\sqrt{3214+\lvert 0.393x-290\rvert}$
y resolution (mm)	98	$\sqrt{2004+\lvert 0.809y-1365\rvert}$
z resolution (mm)	106	$\sqrt{7230+\lvert 0.730z+3211\rvert}$
Angular resolution	$^{+0.13}_{-0.08}$	$^{+0.122}_{-0.020}$
β_{14}	$^{+0.003}_{-0.010}$	$^{+0.005}_{-0.010}$
Energy scale (%)	2.0	1.02
Energy resolution	$^{+0.018}_{-0.016}$	$^{+0.0084}_{-0.0079}$

Initial Solar Neutrino Statistics

Selection	Passing Triggers
Total	12 447 734 554
Low-level cuts	4 547 357 090
Trigger Efficiency	126 207 227
Fit Valid	31 491 305
Fiducial Volume	6 958 079
Hit Timing	2 752 332
Isotropy	2 496 747
Energy	820

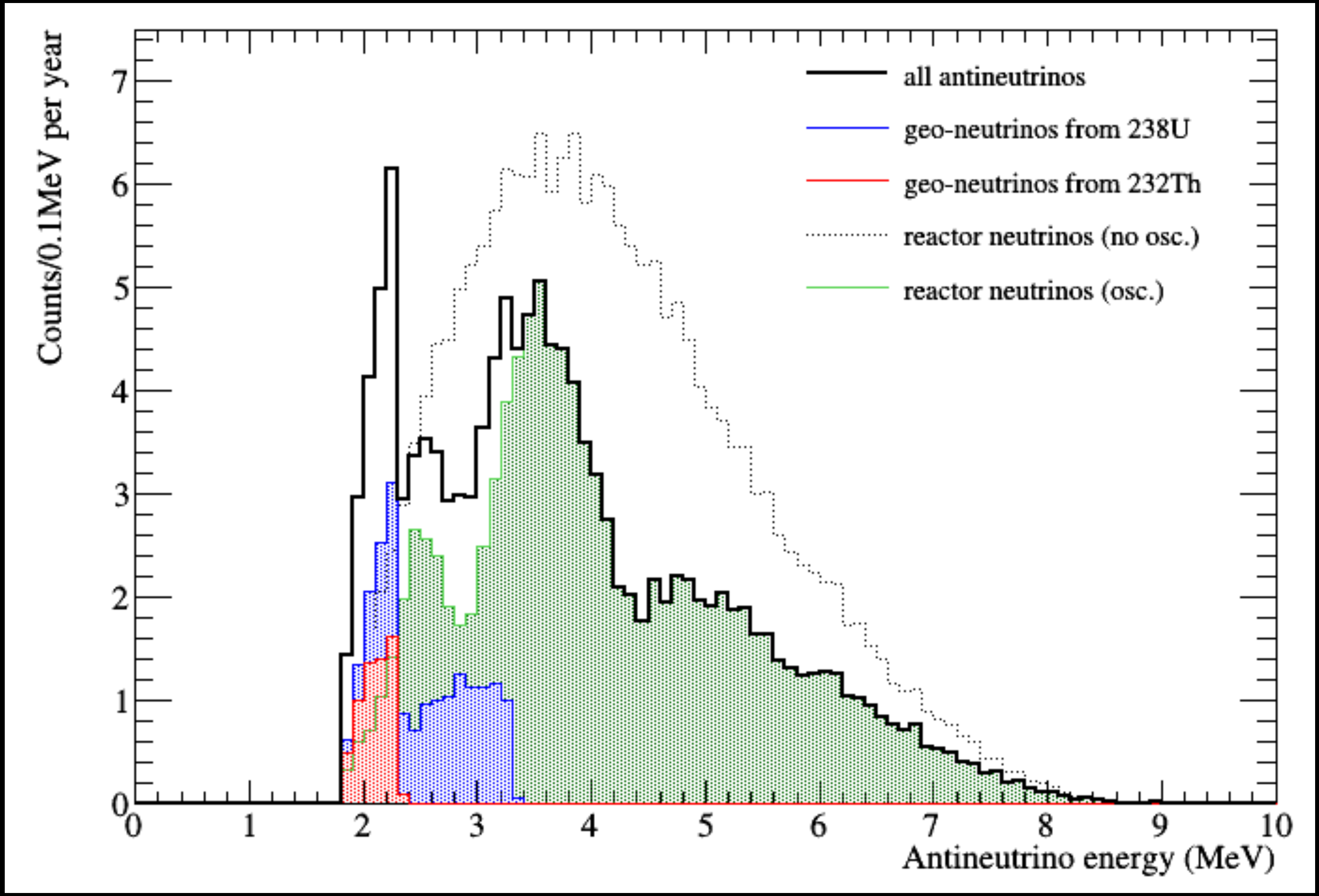
Table II. Dataset reduction for each applied cut. The second column is the number of triggered events from the detector that pass each cut.

Systematic	Effect
Energy Scale	3.9%
Fiducial Volume	2.8%
Angular Resolution	1.7%
Mixing Parameters	1.4%
Energy Resolution	0.4%
Total	5.0%

Table III. Effect of each systematic uncertainty on the extracted solar neutrino flux. Systematic uncertainties with negligible effects are not shown. For asymmetric uncertainties, the larger is shown.

Systematics still being finalised for fully commissioned data set

Antineutrino Spectrum with Geoneutrinos



Scintillator Purification

Contaminant Type	Distillation 220ºC @40 Torr	N2/Steam Stripping 100ºC	Water Extraction
Heavy Metals (radioactive)	Bi, K, Pb, Po, Ra, Th		U, Th, Ra, K, Pb
Dissolved Gases (radioactive)		Ar, Kr, O_2, Rn	
Oxidised Organics (Optical clarity)	Carboxyl groups, 1,4-benzoquinone		
Volatile Liquids (Optical clarity)		Residual water	