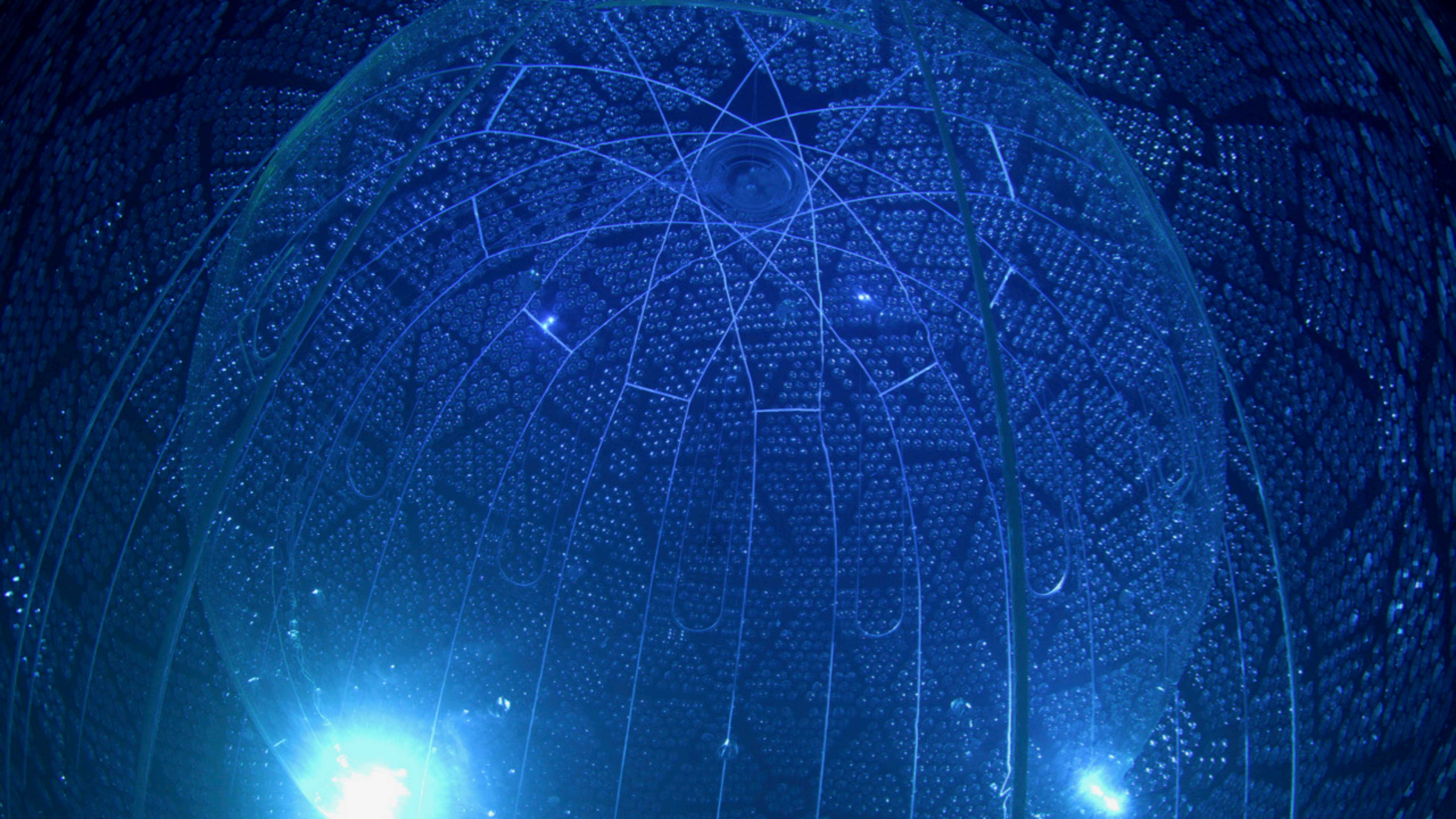
Status and Prospects of the
SNO+ Experiment

Benjamin Tam (for the SNO+ Collaboration)
CAP Congress 2023
19 June 2023



SNO+

A multi-purpose neutrino experiment

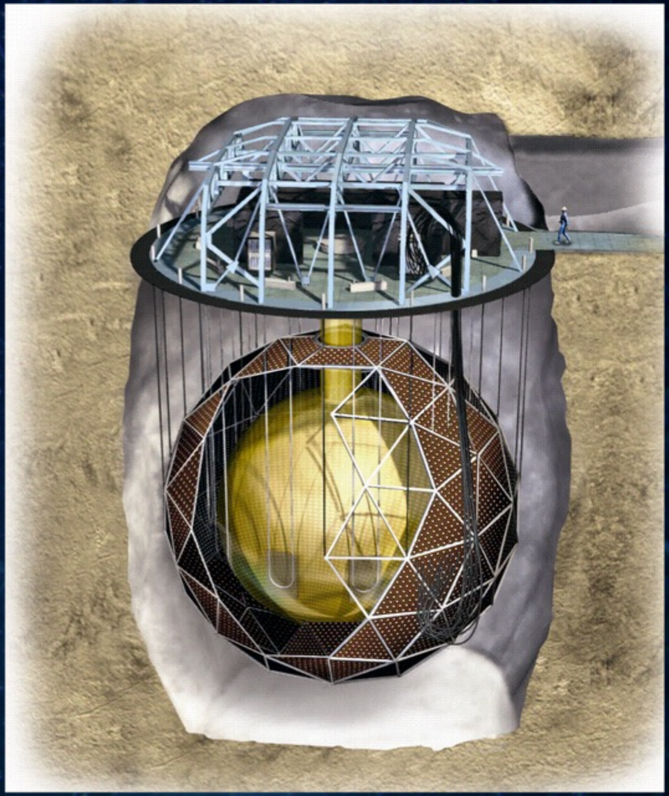
Successor to the Sudbury Neutrino Observatory

Inherited the main detector infrastructure:

- Primary detector body: a 12-m diameter Acrylic vessel
- Outer steel support structure, housing 9800 photomultiplier tubes
- Located in the SNOLAB underground facility

Upgraded with liquid scintillator

- Better light yield



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SNOLAB
Shandong University
University of Sussex
TRIUMF

Primary SNO+ Physics Goal

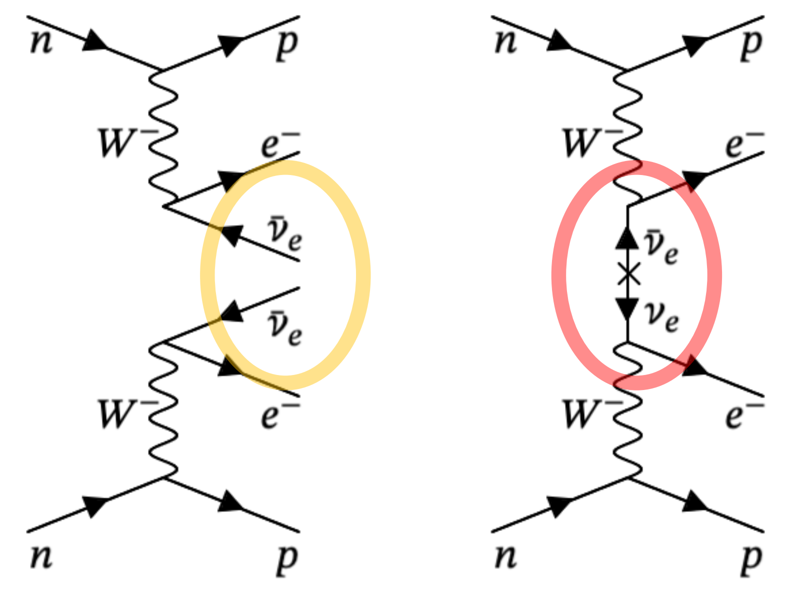
Determining if Neutrinos are Majorana Particles

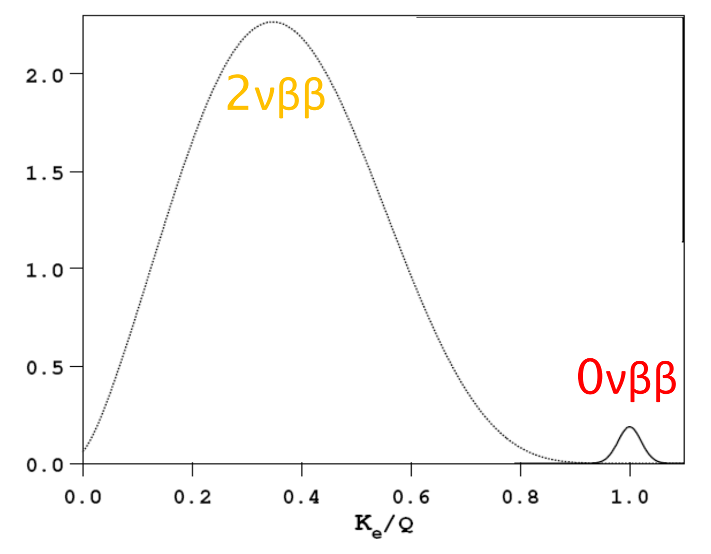
- Neutrinos and Antineutrinos would be the same particle
- Provides satisfying mass mechanism for neutrinos
  - And much more!

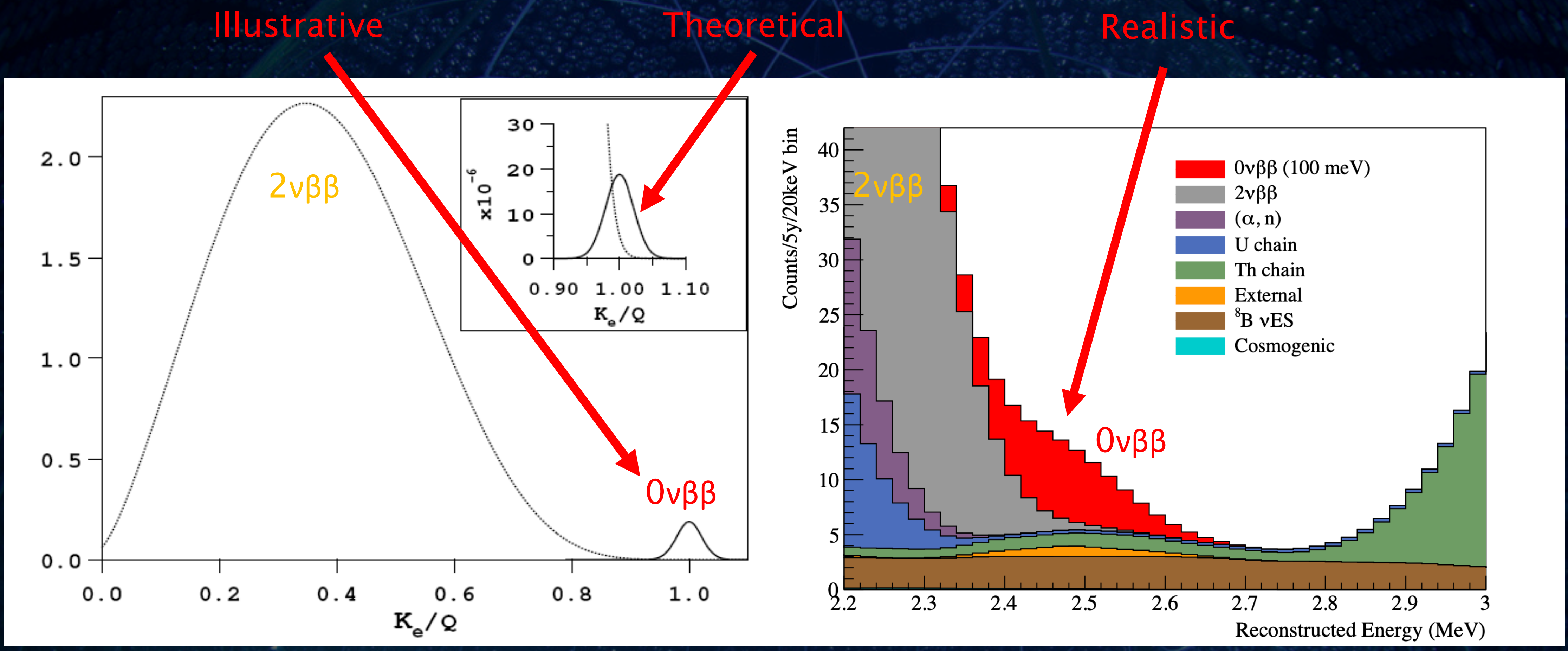
Experimental Methodology

Neutrinoless Double Beta Decay “0νββ”

- Two-neutrino double beta decay exists
  - Releases 2 neutrinos, 2 electrons
- If Majorana, the neutrino is exchanged virtually
  - Releases 0 neutrinos, 2 electrons
- Signature Signal: the measurement of both electrons







Main Experimental Challenge

Suppressing Backgrounds through intense shielding and purification

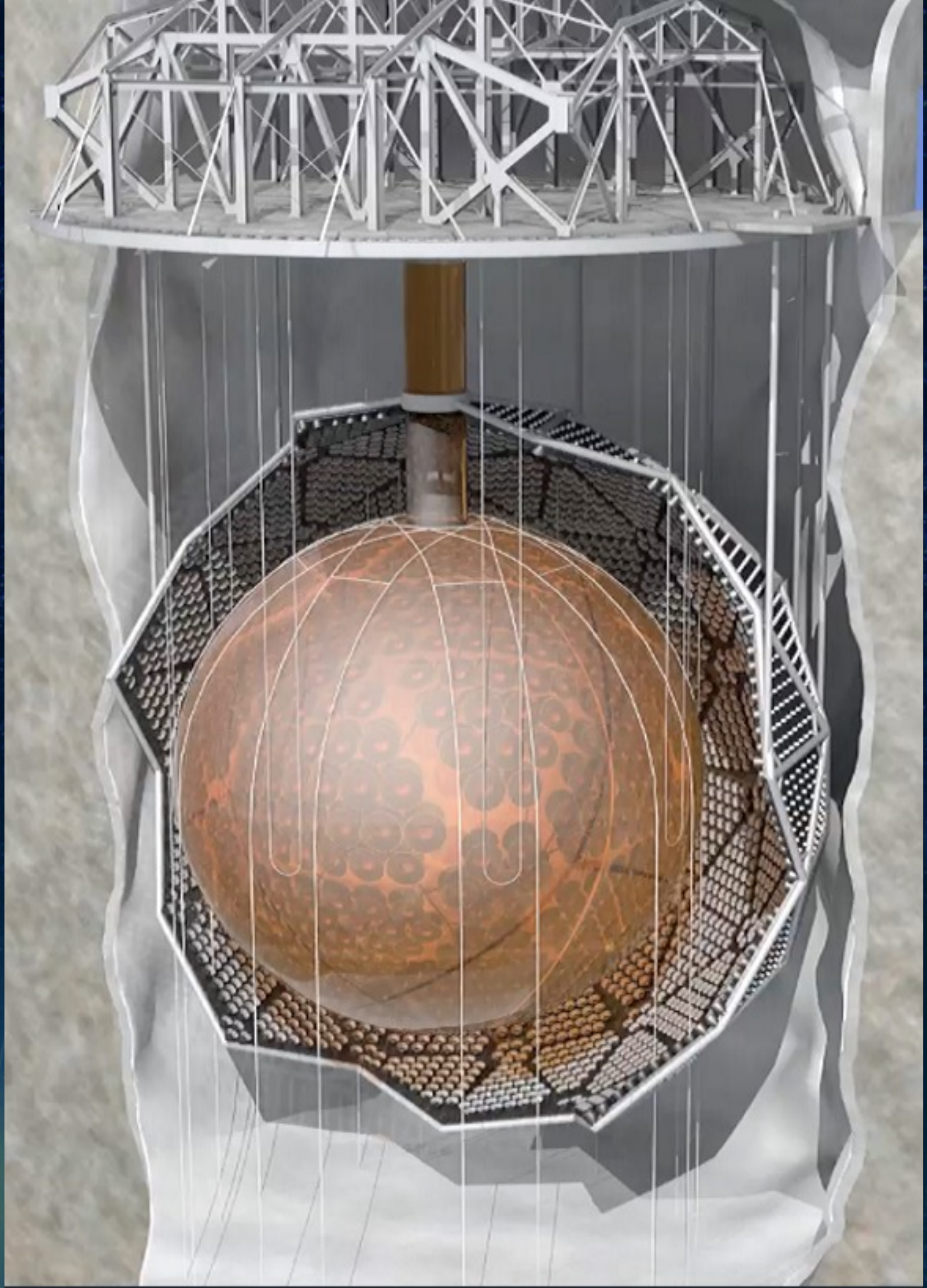
Shielding

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

7000 m^3 external ultrapure water shielding

N_2 Cover Gas blanket across entire detector

Cavity treated with water- and radon-impermeable plastic



Purification

Four chemical plants to treat the various internal and external media

Vigorous QA campaign:
hourly chemical analysis during operations

Recirculation and repurification capabilities for internal and external media

Detector Hardware: JINST 16 P08059

Three Operational Phases based on AV medium

Water Phase

May 2017 - July 2019

905 tonnes ultrapure Water

Scintillator Fill

Scintillator Phase

Started April 2022

780 tonnes liquid scintillator

Te Loading

Tellurium Phase

Deployment 2024

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

- Neutrinoless double beta decay in ^{130}Te

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- Solar neutrinos
- Reactor anti-neutrinos

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

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

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

Wide range of secondary physics capabilities!

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SNO+ Water Phase Complete!

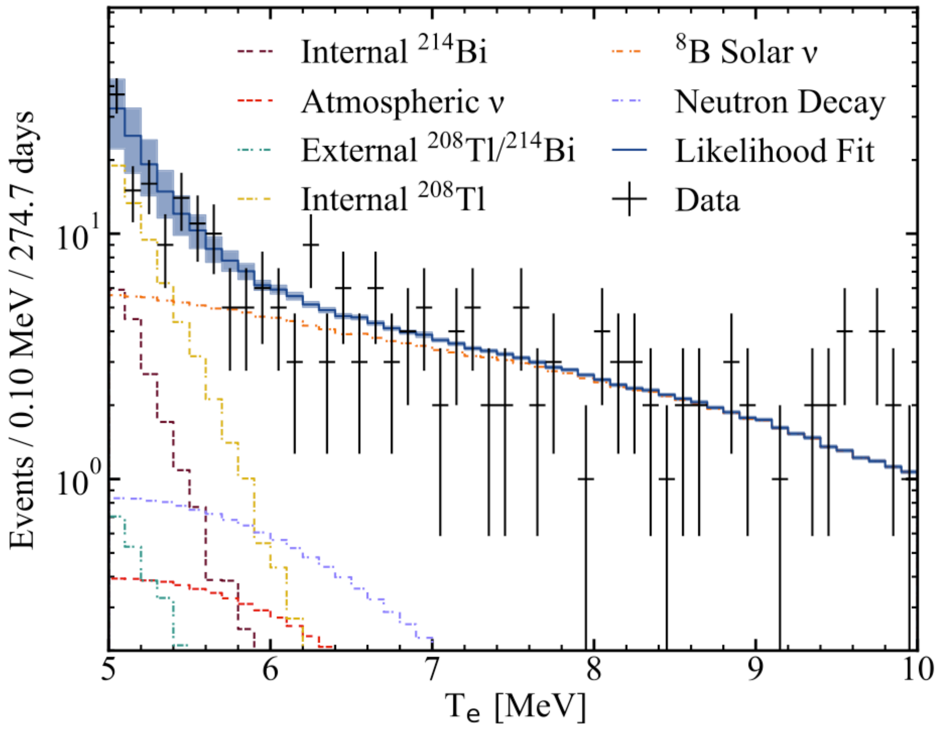
Recent Results – Invisible Nucleon Decay

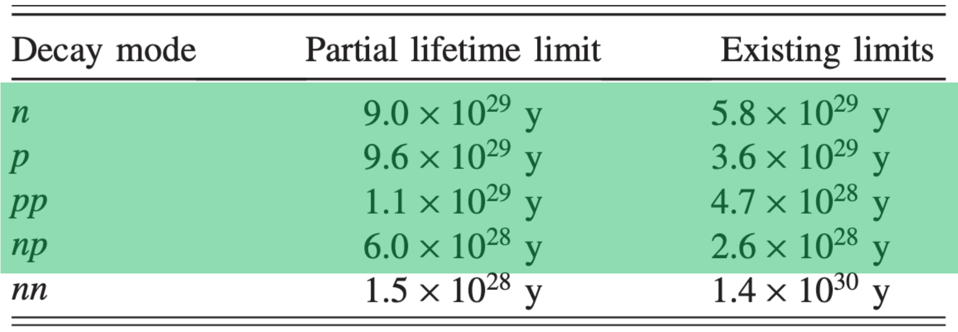
- Nucleon decay modes to final states where no visible energy is deposited

  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

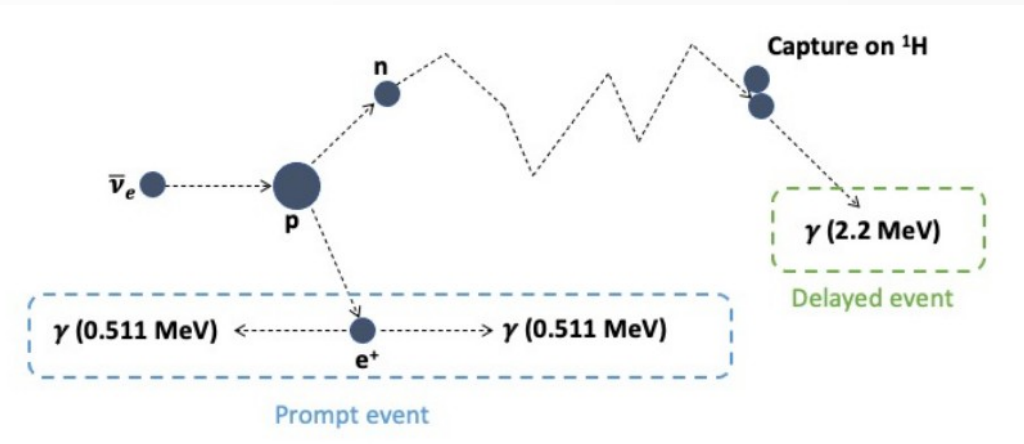




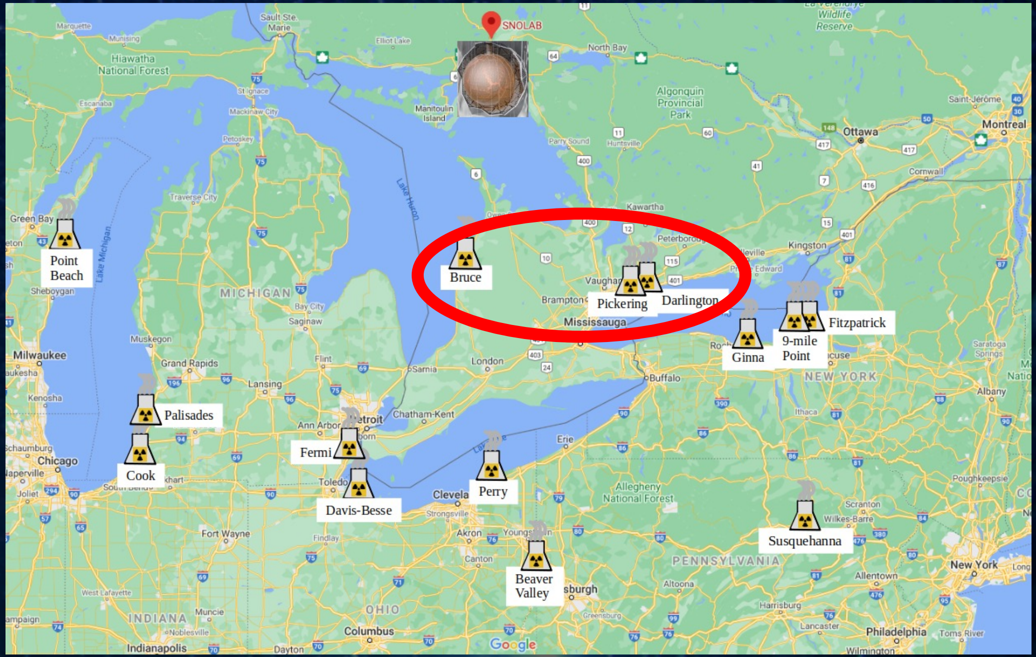
Decay mode	Partial lifetime limit	Existing limits
n	9.0×10^{29} y	5.8×10^{29} y
p	9.6×10^{29} y	3.6×10^{29} y
pp	1.1×10^{29} y	4.7×10^{28} y
np	6.0×10^{28} y	2.6×10^{28} y
nn	1.5×10^{28} y	1.4×10^{30} y

Recent Results – Reactor Antineutrinos

Detection of reactor antineutrinos through inverse beta decay (IBD)



- 60% of IBD events occur from 3 reactors (18 cores) 240km, 340km, 350km away
- Neutron-Proton capture cross-section and timing measured, 50% detection efficiency
  Phys.Rev.C 102, 014002
- First measurement of reactor antineutrinos using pure water
  Phys.Rev.Lett 130, 091801
    PRL Editor’s Choice
    APS Physics Magazine Highlight



Recent Results – Solar Neutrinos

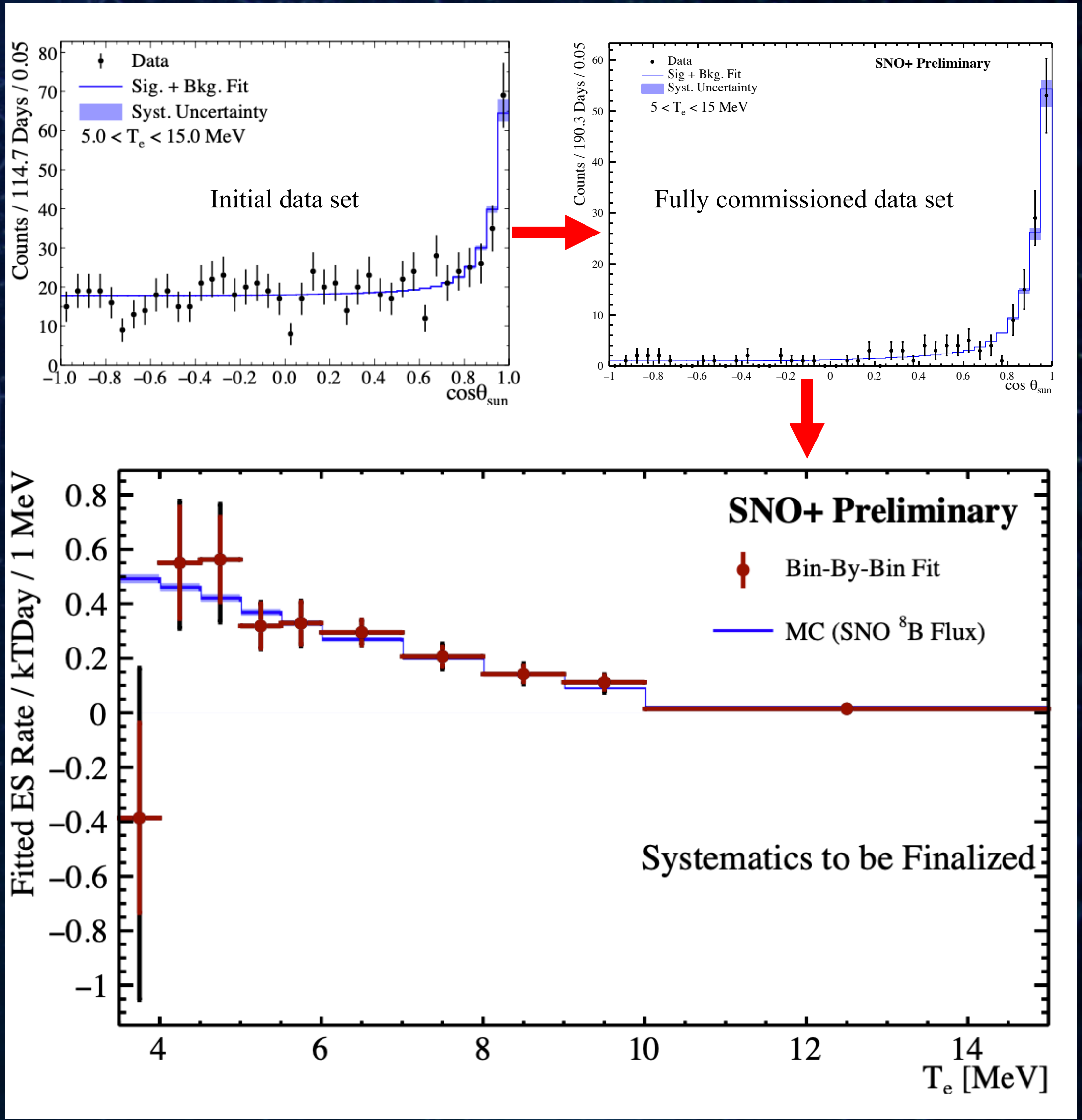
- ^{8}B Solar Neutrino flux measured with initial commissioning data
  Phys.Rev.D 99, 012012

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

  - 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

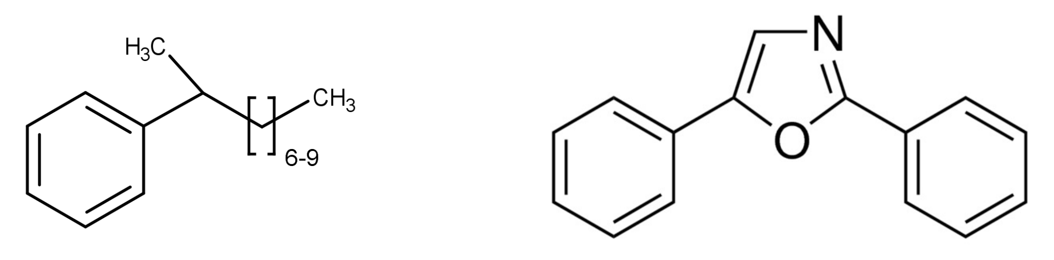
- Analysis on new data set complete
  - New data set uses fully commissioned detector
  - N_2 cover gas to suppress Rn backgrounds

- Publication submission imminent!



Liquid Scintillator

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



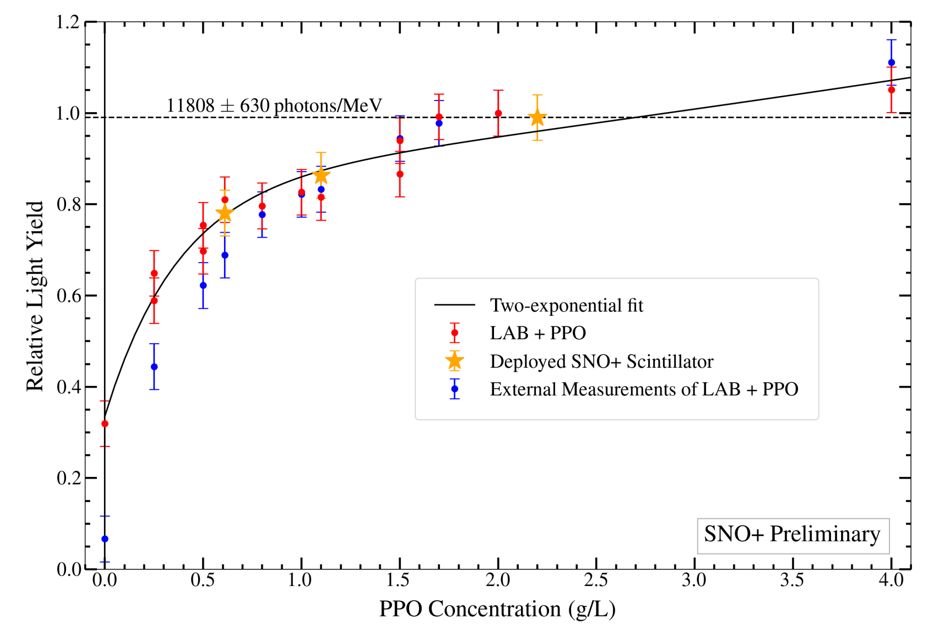
- LAB developed by SNO+
  - Existing liquid scintillators not sufficiently compatible with acrylic
  - Now used in numerous other experiments
- PPO acts as a fluor emitting in the ~390nm range
- >50x higher light yield than water

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
- Ultra-purity of scintillator verified through extensive suite of hourly measurements during filling (~6000 samples analysed)



Scintillator Fill Completed

April 29, 2022

Physics programme underway

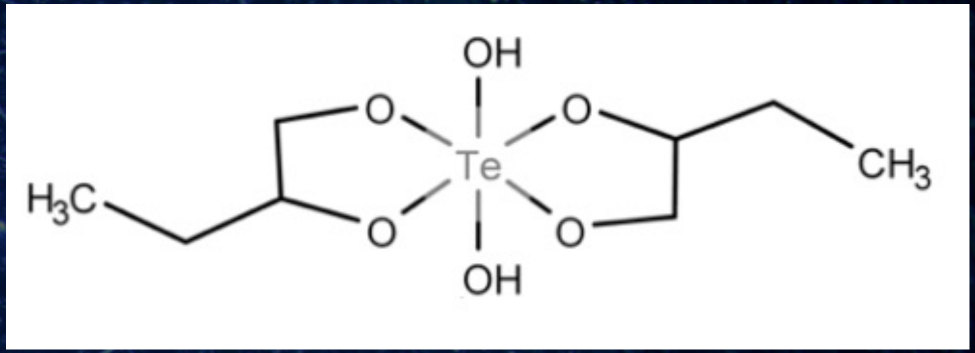
"The Last Sample"

Tellurium Loading

Main SNO+ goal: searching for $0\nu\beta\beta$ in ^{130}Te

- Novel metal-loading technique to dope SNO+ LS with ^{130}Te finalised
  - Achieved by diolising telluric acid (TeA)
  - Forms Tellurium Butanediol (TeBD) that dissolves in LAB

  NIM.A. 1051:168204



- Additives planned to boost light yield and stability:
  - 1,4-bis(2-methylstyryl)benzene (bis-MSB)
  - Butylated hydroxytulene (BHT)
  - N,n-dimethydodecylamine (DDA)

Planned Cocktail Composition:

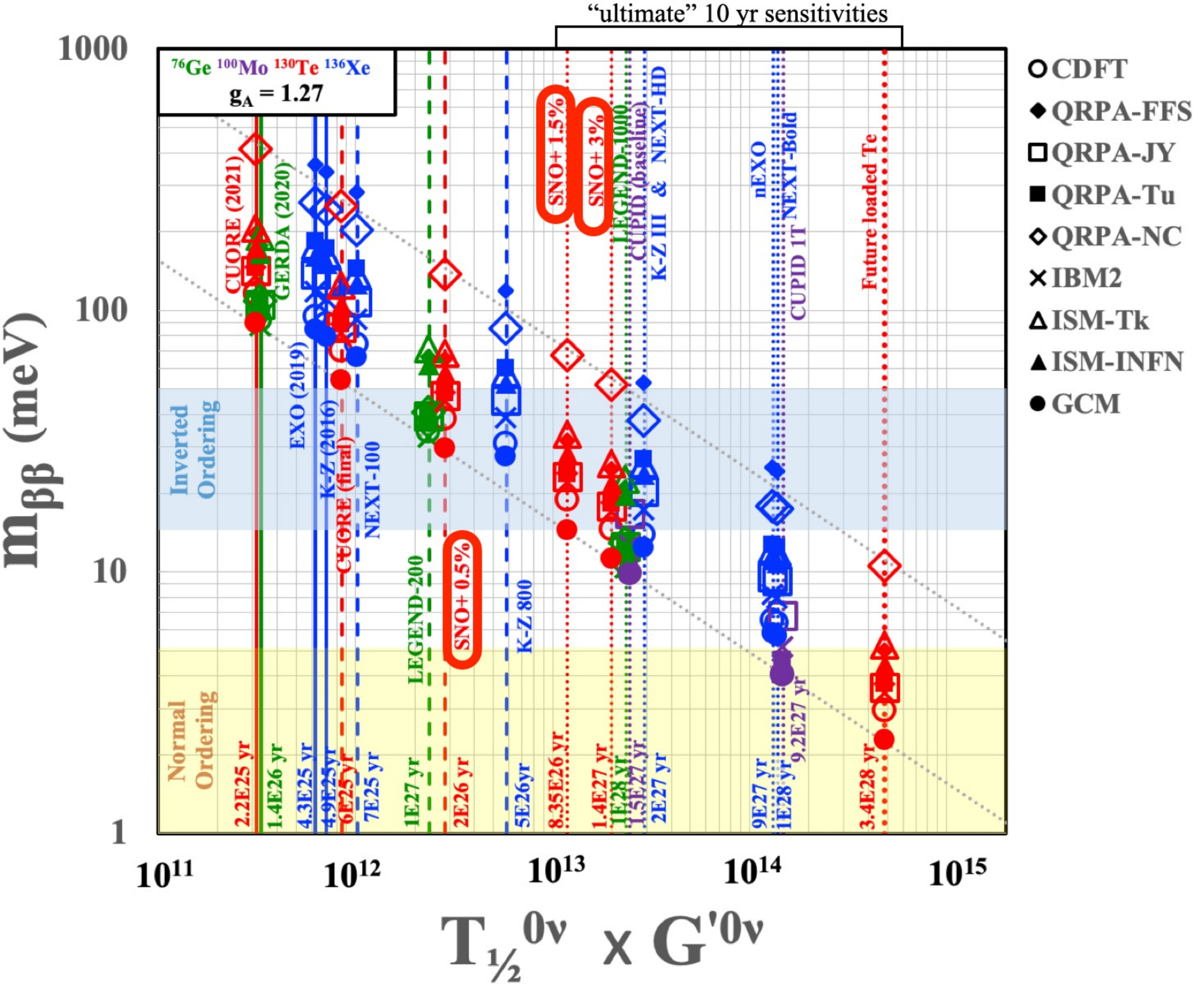
LAB + 2.2 g/L PPO
+ 5 mg/L bis-MSB
+ 8 µg/L BHT
+ DDA (0.5 molar ratio DDA:Te)
+ TeBD

🟩 Already deployed!
🟨 Being deployed this week!
🟧 In procurement
🟥 Procured and awaiting purification

Tellurium Phase - 0νββ

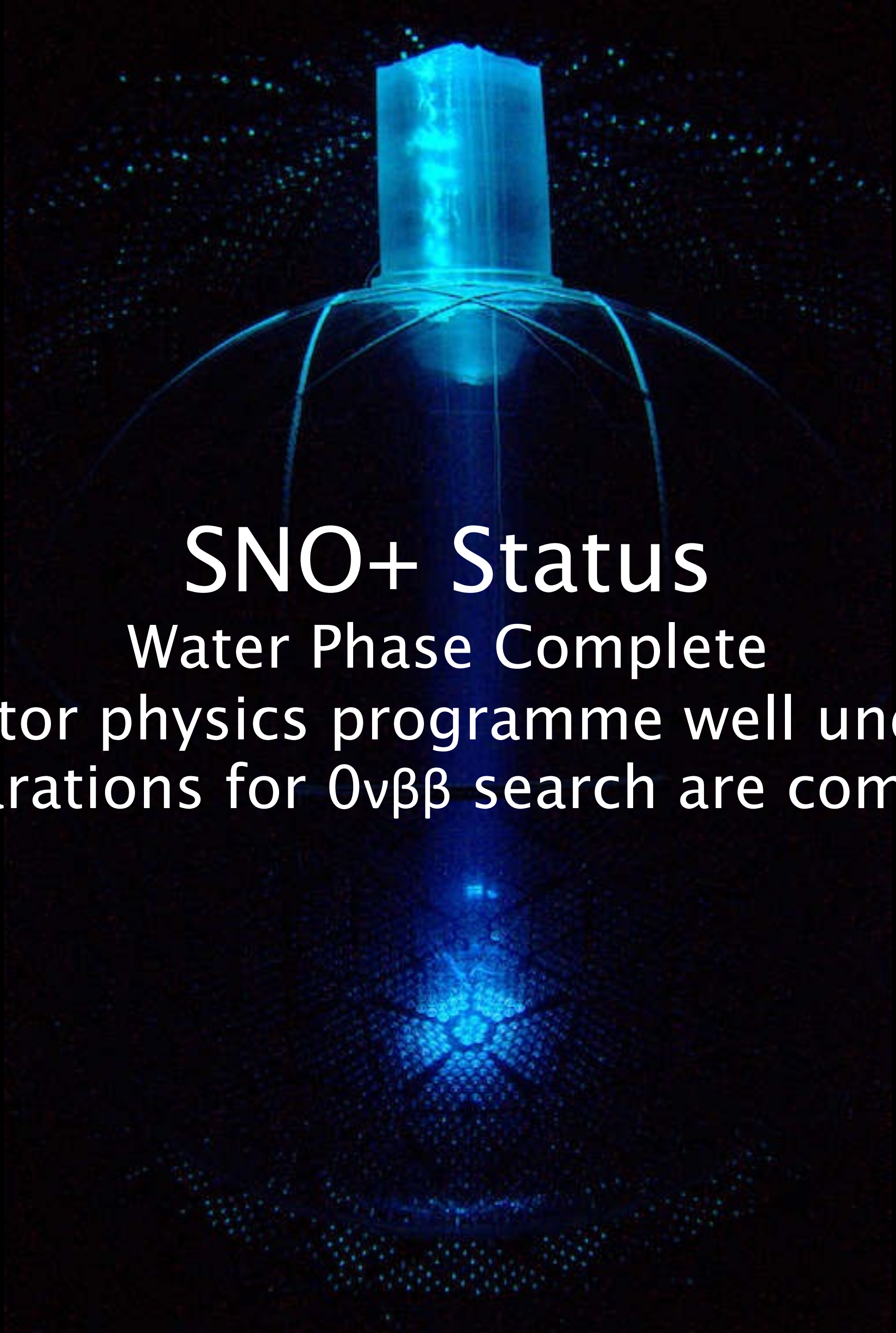
- Tellurium will be purified and deployed using 2 additional plants underground
  - Plant construction complete, field test imminent
- Initial loading of 0.5% ^{nat}Te
  - ^{130}Te has a natural abundance of 34%
- Further loading planned and possible

  Scale-up is in late stages of development



Initial deployment planned 2024

Only planned tonne-scale search with Te at this time



SNO+ Status

Water Phase Complete

Scintillator physics programme well underways

Preparations for 0νββ search are complete

Backups

Improved Nucleon Decay Statistics

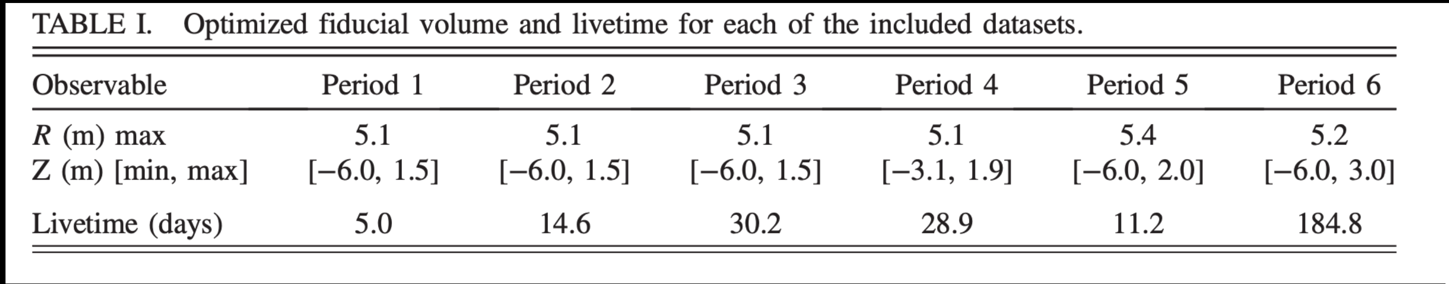
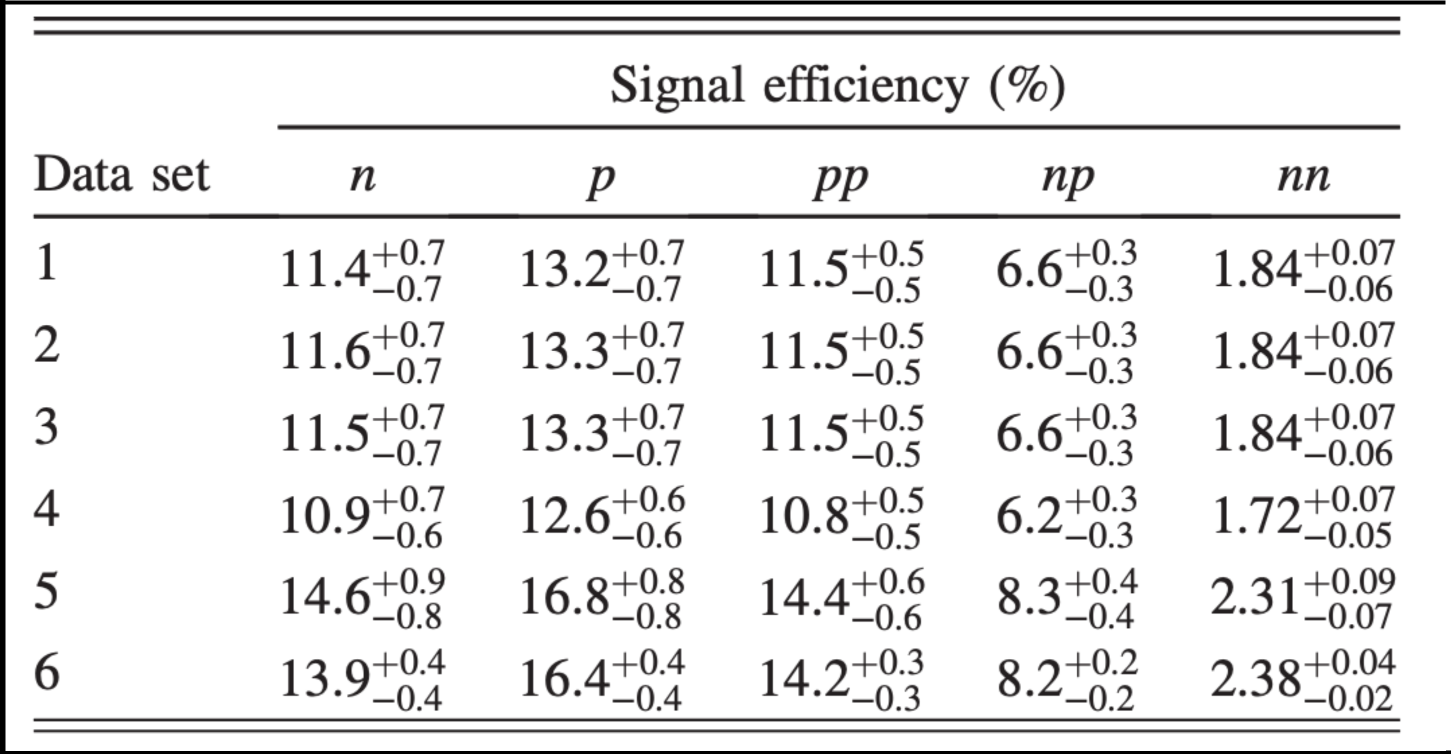


TABLE I. Optimized fiducial volume and livetime for each of the included datasets.

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	$13.9^{+0.4}_{-0.4}$	$16.4^{+0.4}_{-0.4}$	$14.2^{+0.3}_{-0.3}$	$8.2^{+0.2}_{-0.2}$	$2.38^{+0.04}_{-0.02}$

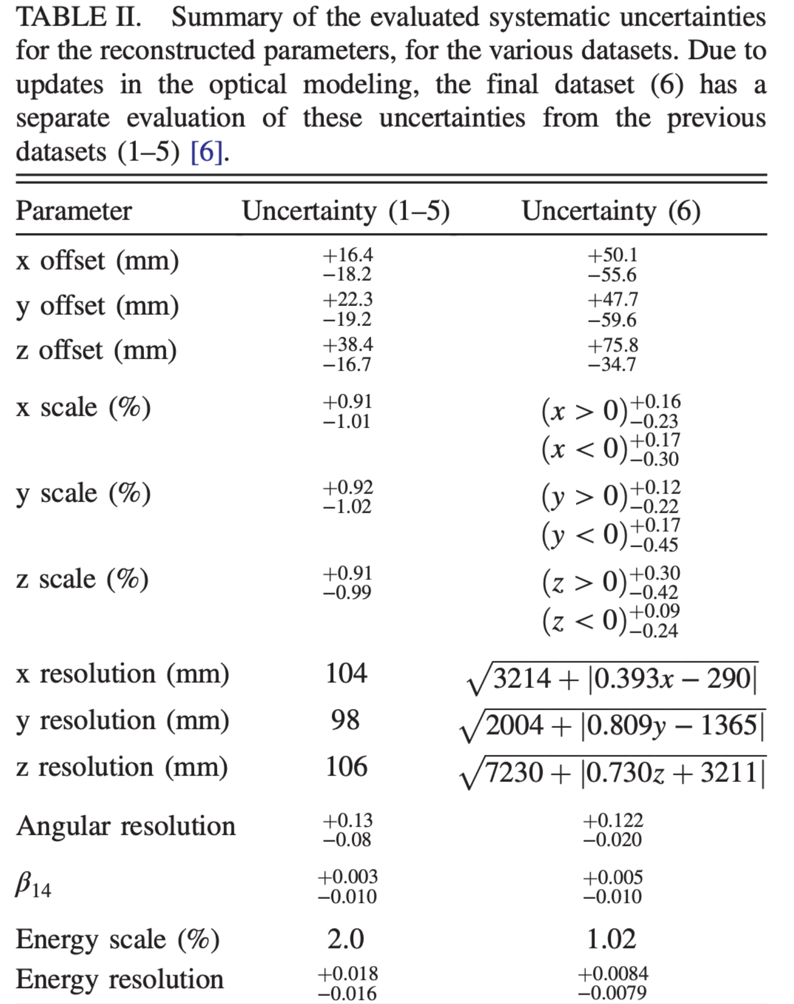
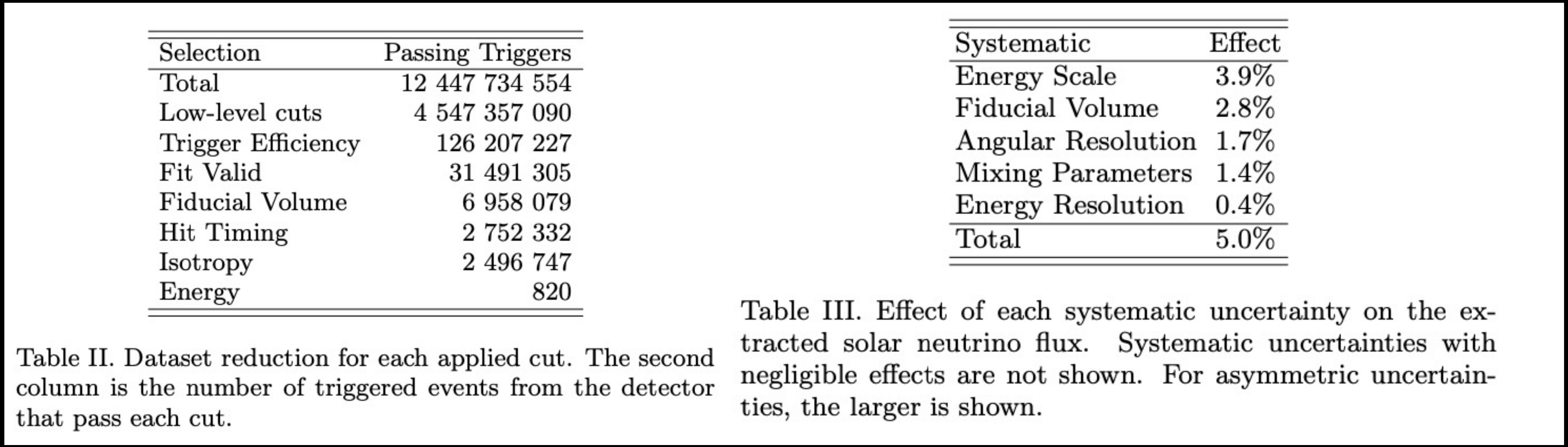


TABLE II. Summary of the evaluated systematic uncertainties for the reconstructed parameters, for the various datasets. Due to updates in the optical modeling, the final dataset (6) has a separate evaluation of these uncertainties from the previous datasets (1–5) [6].

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.

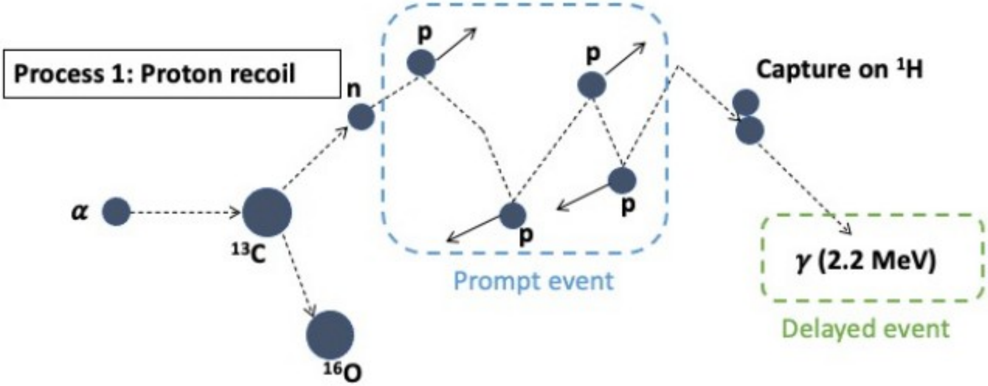
Systematics still being finalised for fully commissioned data set

Scintillator Purification

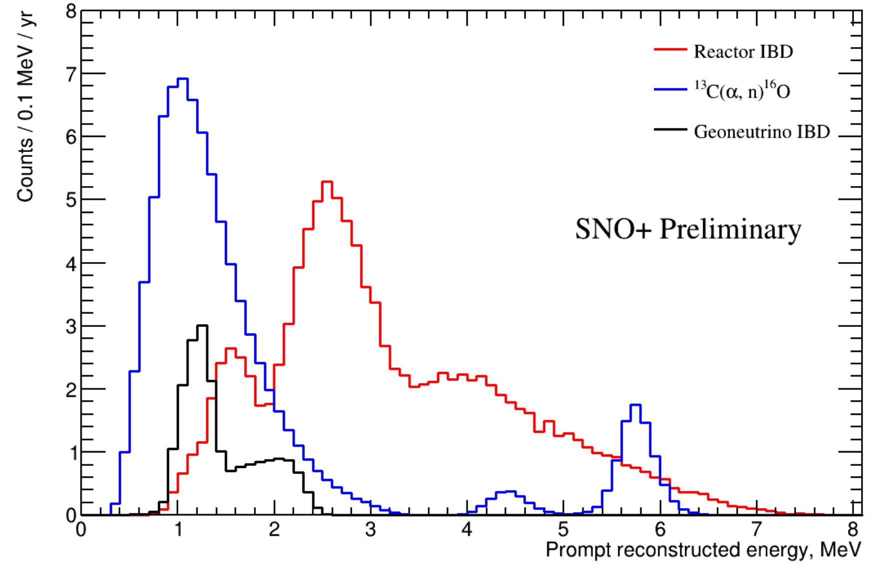
Contaminant Type	Distillation 220ºC @40 Torr	N2/Steam Stripping 100ºC	Water Extraction
Heavy Metals (radioactive)	Bi, K, Pb, Po, Ra, Th		U, Th, Ra, K, Pb
Dissolved Gases (radioactive)		Ar, Kr, O_2, Rn	
Oxidised Organics (Optical clarity)	Carboxyl groups, 1,4-benzoquinone		
Volatile Liquids (Optical clarity)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

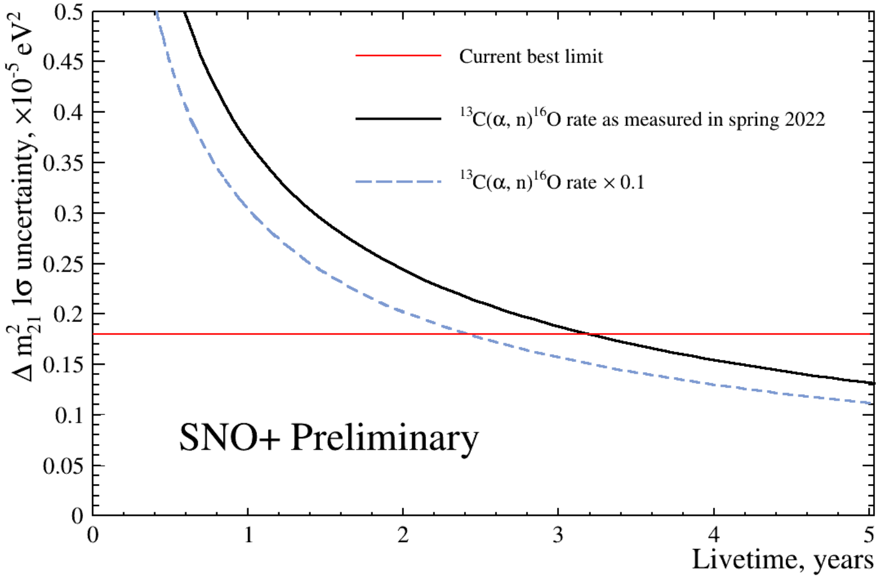
Scintillator Phase - Reactor Antineutrinos

- 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



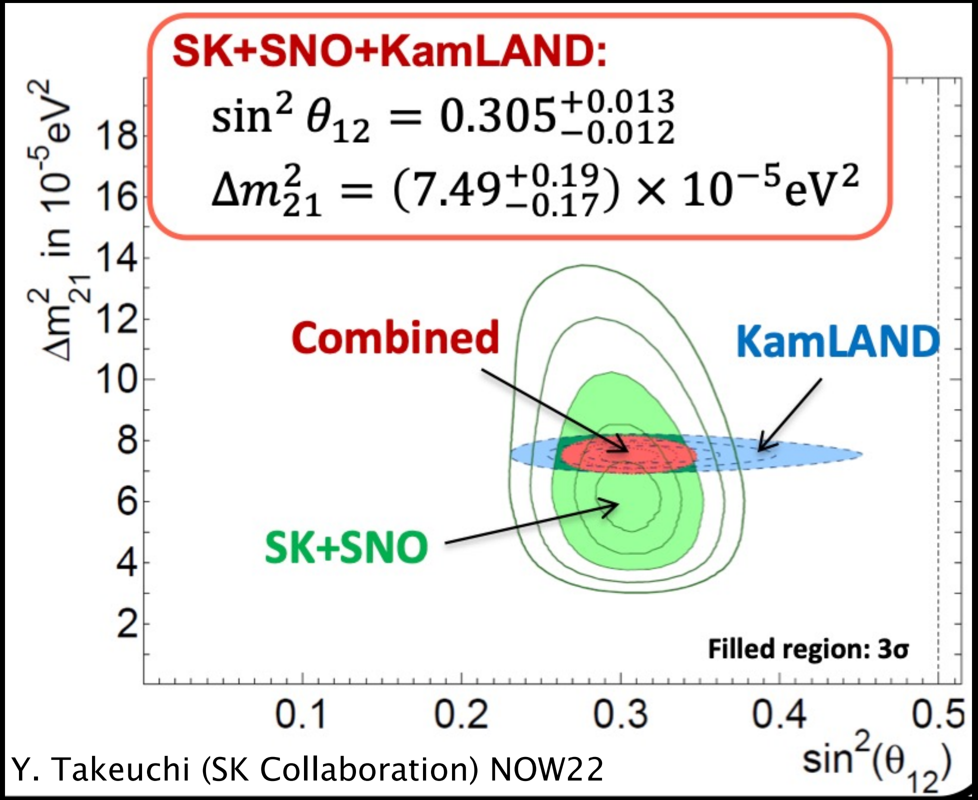


Scintillator Phase - Reactor Antineutrinos

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

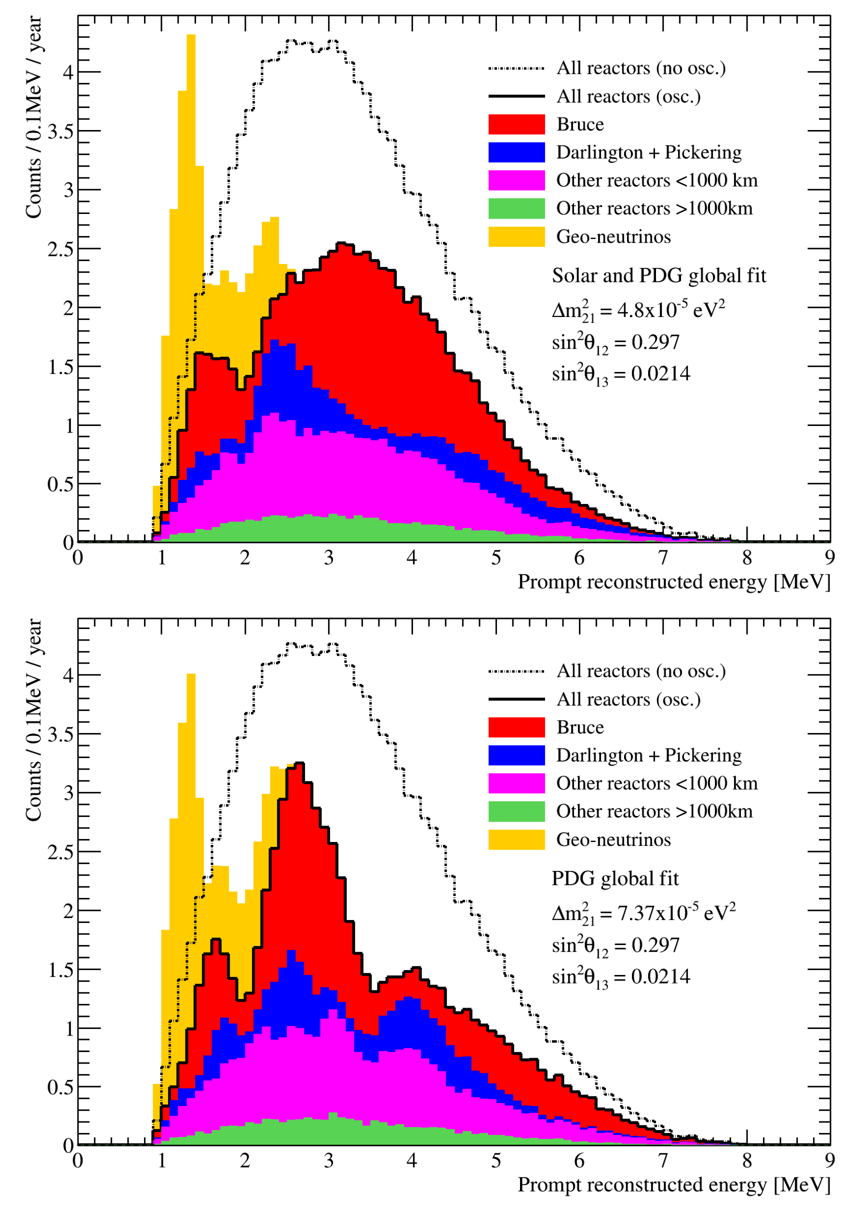


SK+SNO+KamLAND:

$$\sin^2\theta_{12} = 0.305^{+0.013}_{-0.012}$$

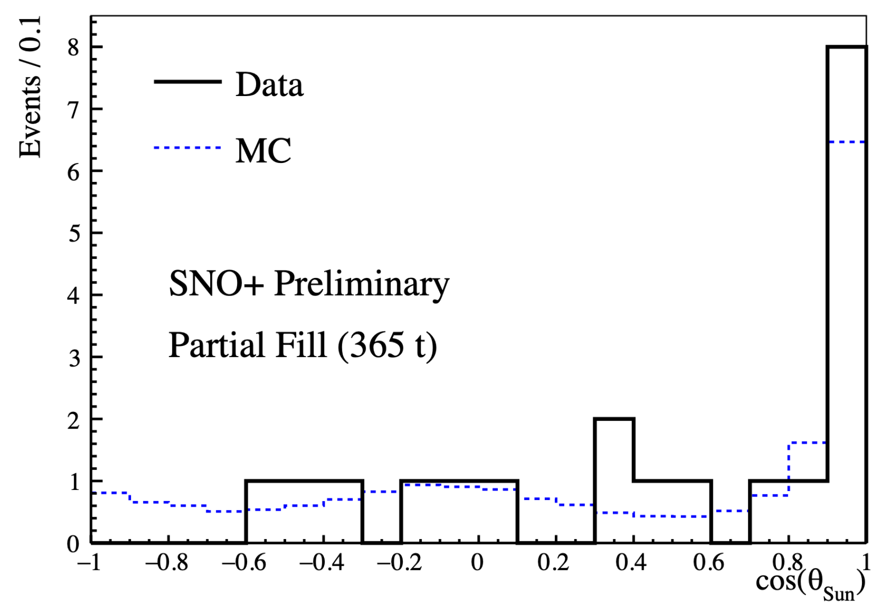
$$\Delta m^2_{21} = (7.49^{+0.19}_{-0.17}) \times 10^{-5}\mathrm{eV}^2$$

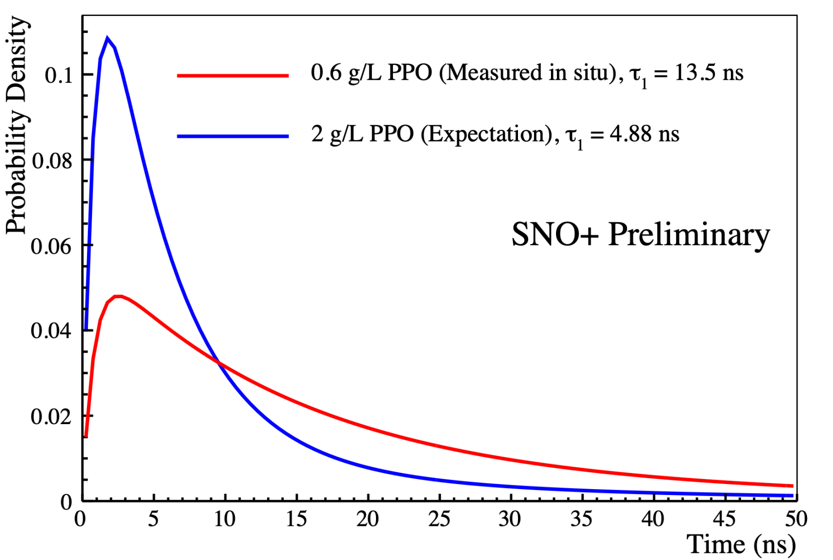
Y. Takeuchi (SK Collaboration) NOW22



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)
- May also be possible with nominal PPO concentration (2.2 g/L)
- Will enhance solar neutrino analyses in the scintillator phase





Antineutrino Spectrum with Geoneutrinos