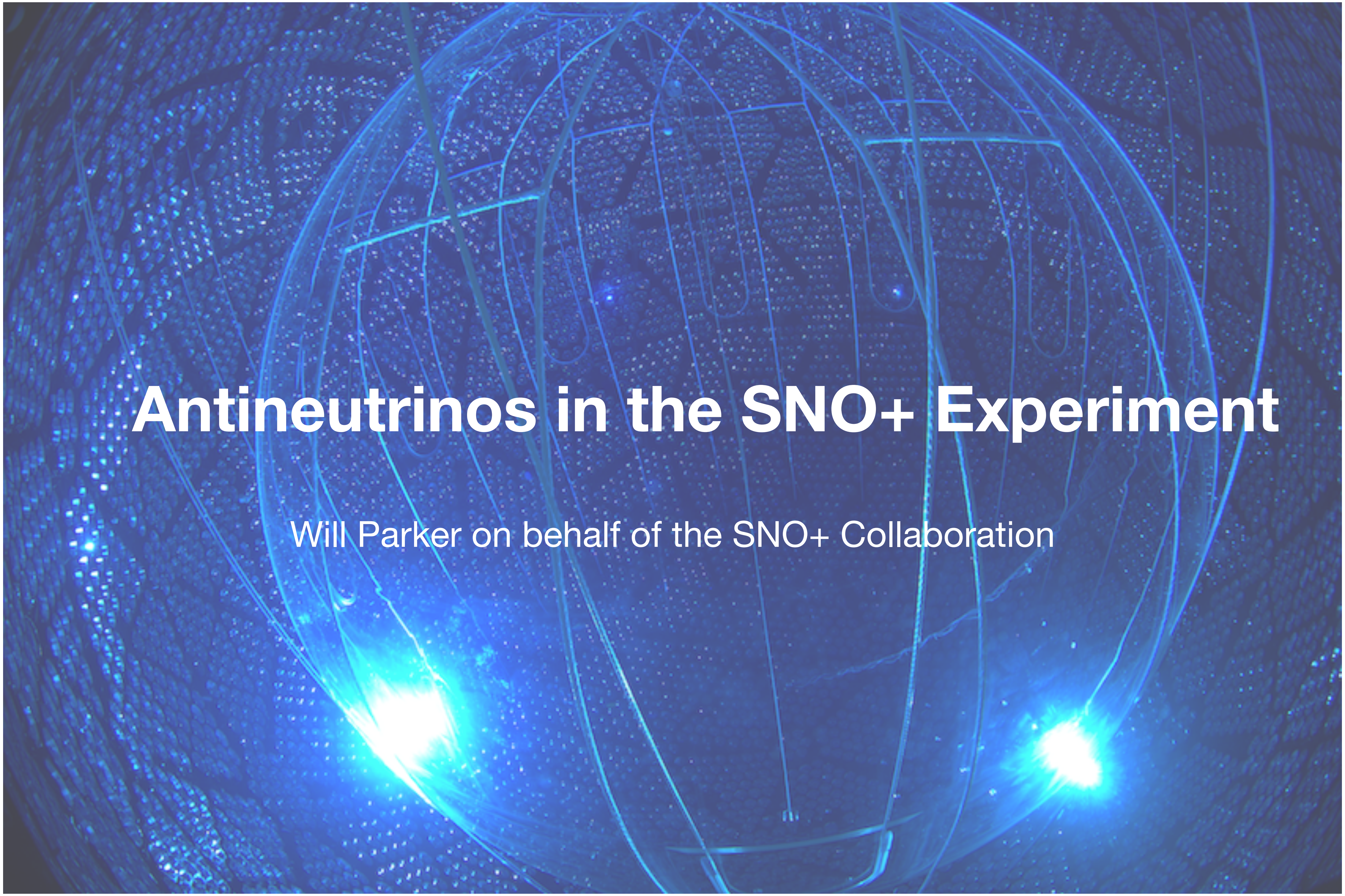
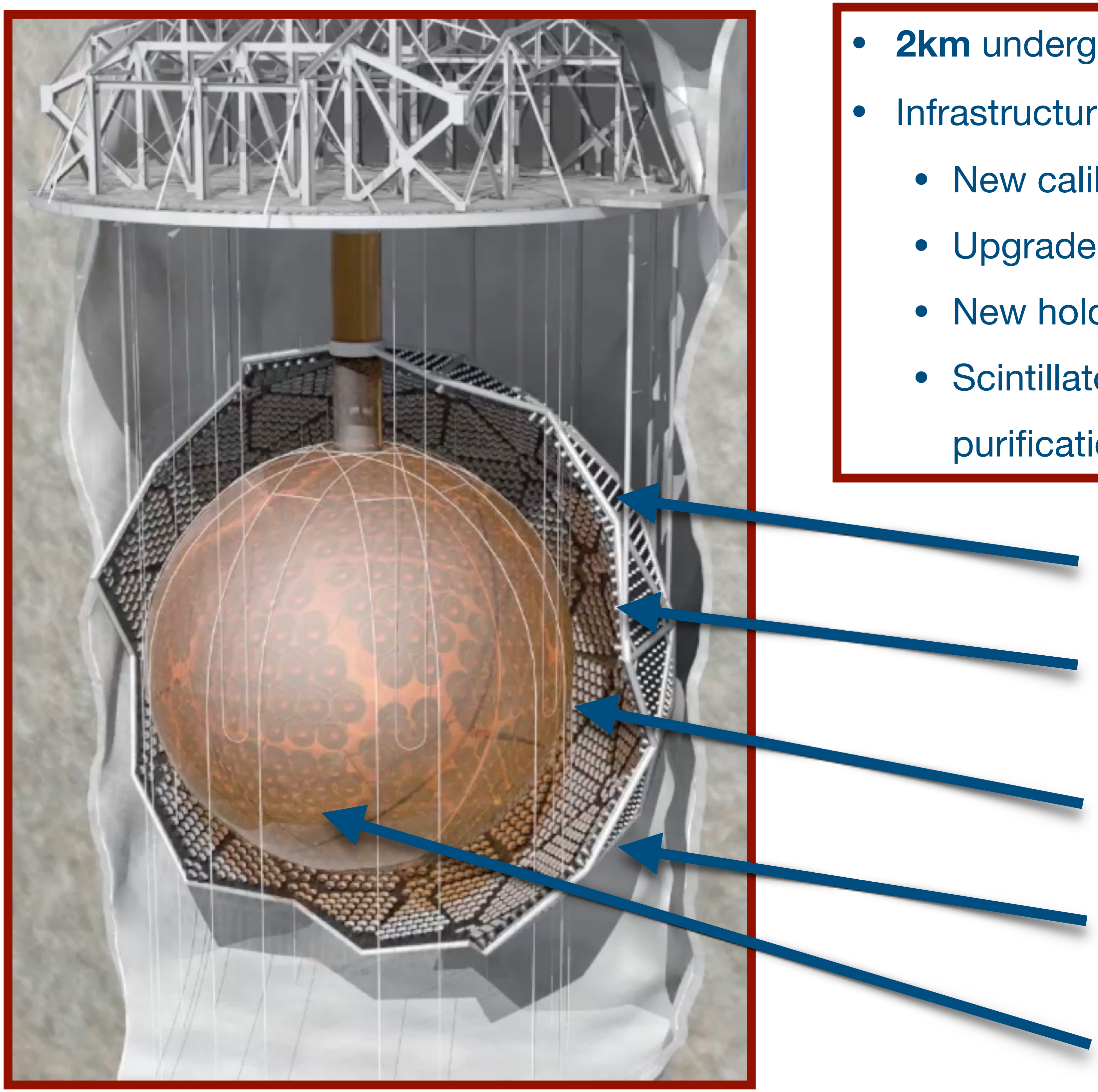


Antineutrinos in the SNO+ Experiment

Will Parker on behalf of the SNO+ Collaboration

The SNO+ Experiment

- **2km** underground in **SNOLAB**, Canada
- Infrastructure repurposed from **SNO**:
    - New calibration systems
    - Upgraded DAQ and electronics
    - New hold-down ropes
    - Scintillator plant + Tellurium synthesis and purification



~9300 PMTs

18 m diameter PMT Support Structure

12 m diameter Acrylic Vessel

7 kt ultra pure water shielding

780 t Liquid Scintillator to be loaded with ^{130}Te for $0\nu\beta\beta$

More info in: JINST 16 P08059 (2021) https://doi.org/10.1088/1748-0221/16/08/P08059

SNO+ Phases

Water Phase

2017-2019

905t Ultra Pure Water

Partial Fill Phase

Mar-Oct 2020

320 t (47%) Scintillator

0.6 g/l PPO

Full Fill Phase

2022 - Present

Fully filled with Scintillator

2.2 g/l PPO

2.2 mg/l bisMSB

Tellurium Phase

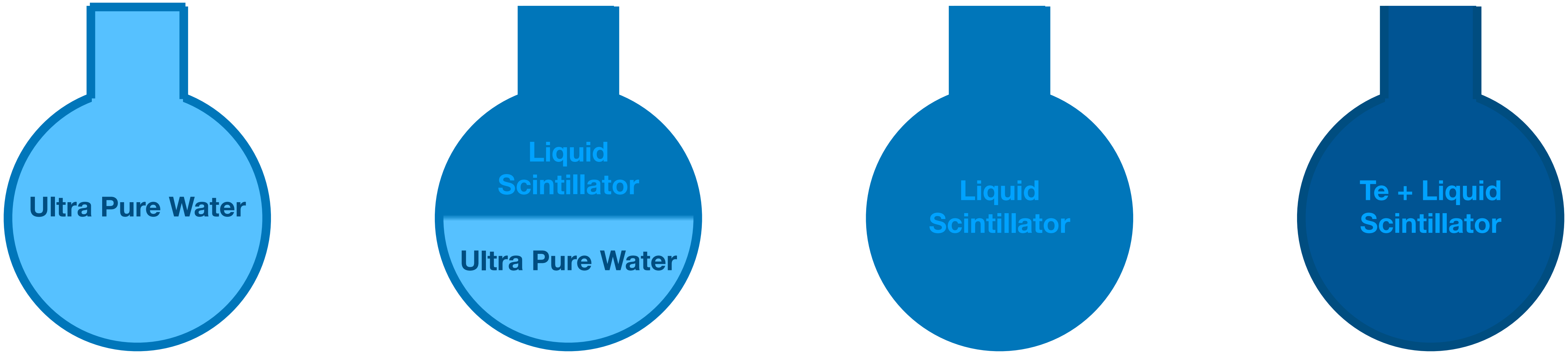
2025

Fully filled with Scintillator

2.2 g/l PPO

2.2 mg/l bisMSB

0.5% Loading of Tellurium initially



Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+

Physical Review Letters (130) 091801, 2023

Initial Measurement of Reactor Antineutrino Oscillation at SNO+

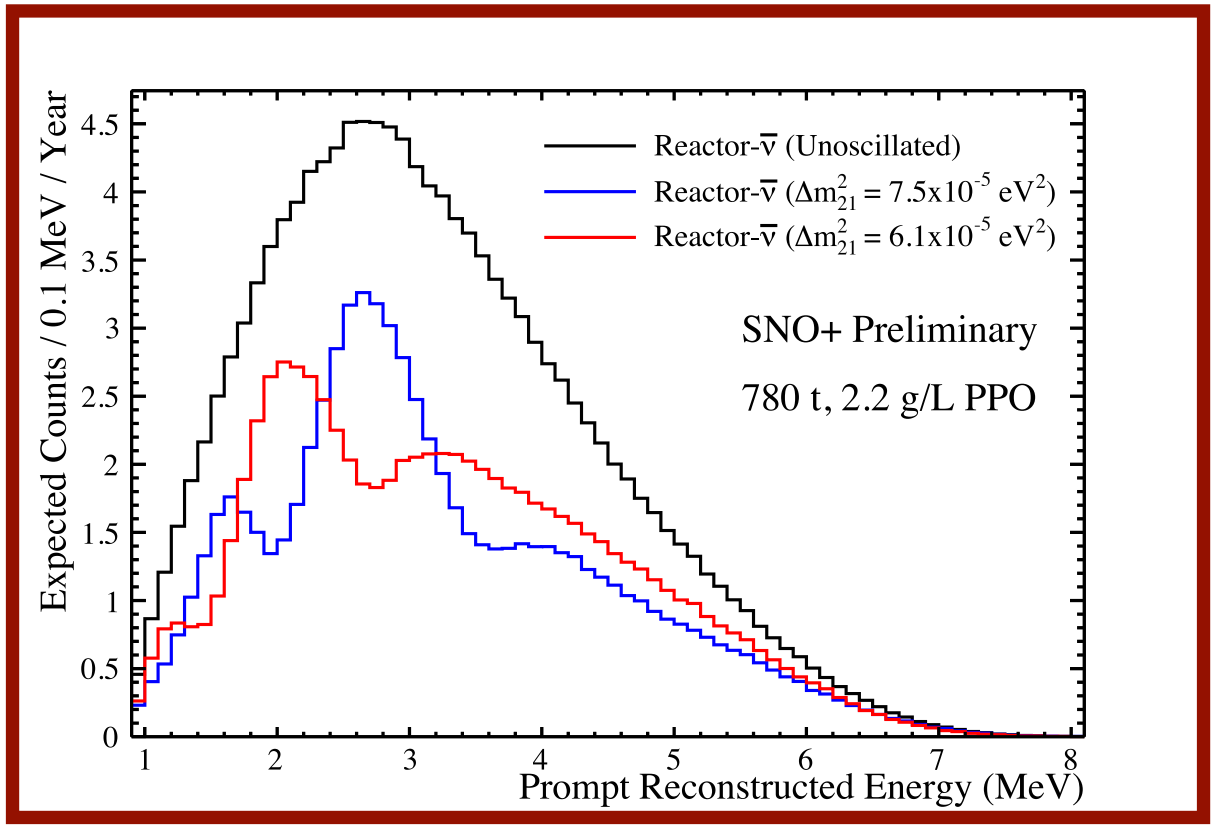
https://arxiv.org/abs/2405.19700

Measurement of Reactor Antineutrino Oscillation and Geoneutrino Flux

Preliminary results shown at Neutrino 2024, and this talk!

Antineutrino Sources: Reactors

- **60%** of reactor antineutrino flux comes from three PHWRs in Ontario, with baselines **240-350 km**
- Sensitive to Δm^2_{21} and θ_{12}
- Energy resolution allows spectral features to be resolved
- Current **1.5 σ-tension** between solar ($6.1^{+0.95}_{-0.81} \times 10^{-5}$ eV²) and reactor ($7.53^{+0.18}_{-0.18} \times 10^{-5}$ eV²) measurements of Δm^2_{21}
- Remaining flux from ~100 cores in the USA



Antineutrino Sources: Reactors

- Reactor antineutrino flux from β decay of **4 isotopes**: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- These isotopes have different fission fractions in **three modelled reactor types**
- **PHWRs** have continuous refuelling, and modelled with daily power information
- **PWR/BWRs** modelled with monthly power information
- Combine thermal power outputs with average energy emitted per fission to calculate antineutrino flux

Reactor Antineutrino Flux Uncertainties

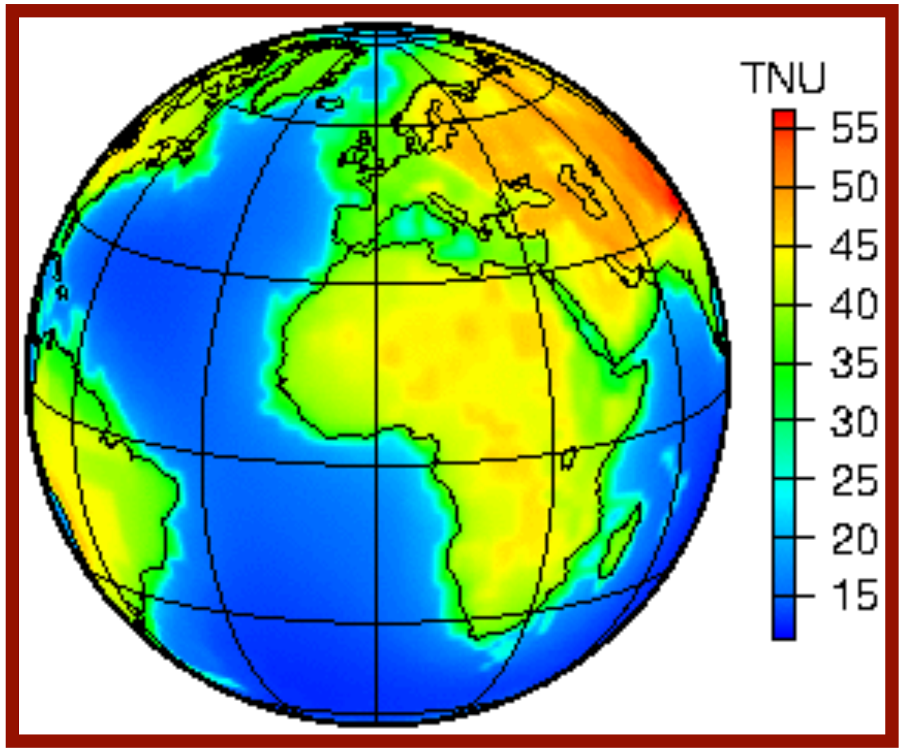
Source	Uncertainty
Emission Spectrum	2.4%
IESO vs. IAEA Power	1.0%
Fission Fraction	0.6%
Reaction Power	0.5%
Target Protons	0.5%
IBD Cross Section	0.4%
Spent Fuel	0.3%
Non-equilibrium	0.2%
Energy/Fission	0.2%
Fixed θ_{13}	0.14%
Total	**2.8%**

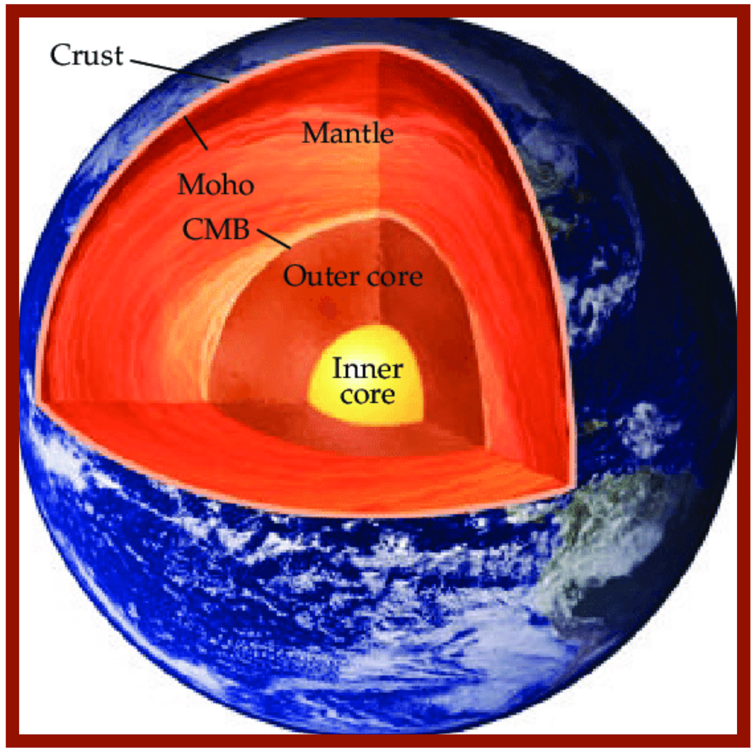
Fission Fractions

	^{235}U	^{238}U	^{239}Pu	^{241}Pu
PHWR/ CANDU	52%	5%	42%	1%
PWR & BWR	57%	8%	30%	6%

Antineutrino Sources: Geoneutrinos

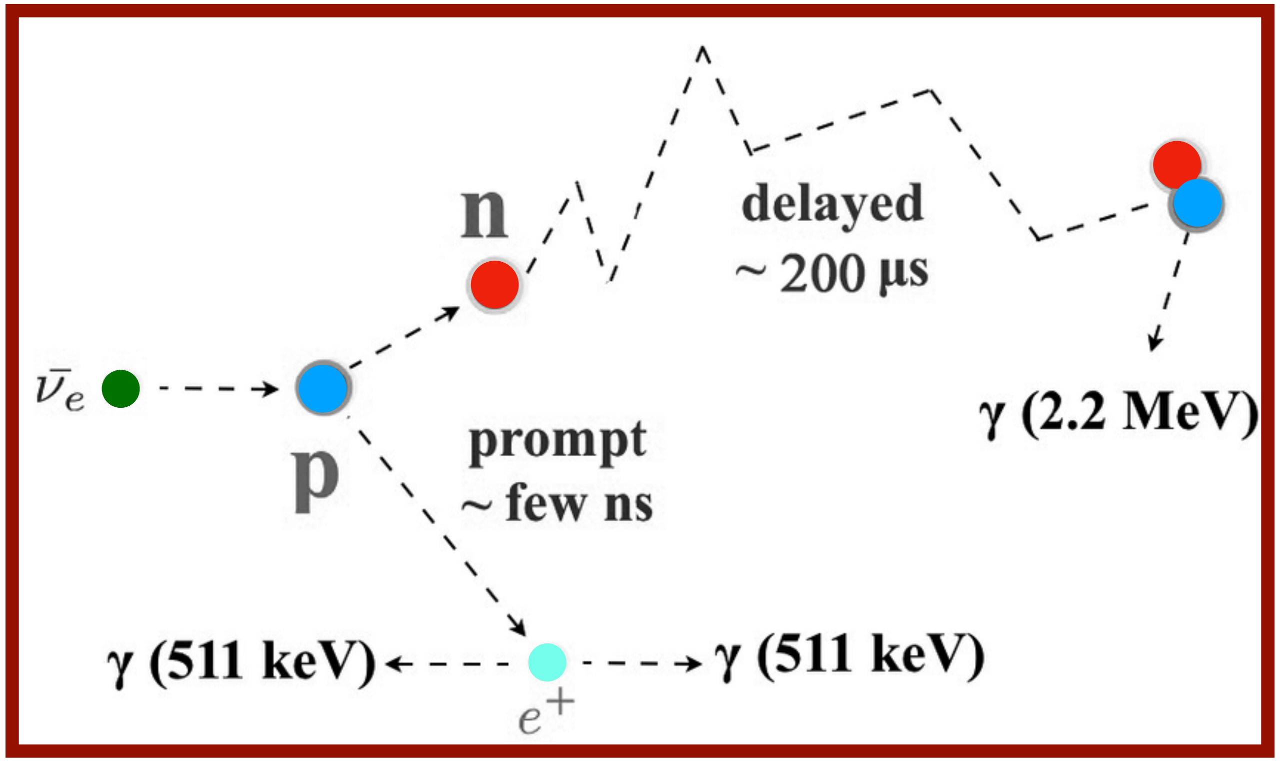
- Produced by radioactive decay of ^{238}**U**, ^{232}**Th** and ^{40}**K** in the Earth's crust and mantle
- Indistinguishable from reactor antineutrinos
- Flux depends on local geology and **geological model** introducing large uncertainties
    - Simulated using Mid-Q model, but with no prior constraints (other than U/Th ratio)
- SNO+ will make **first measurement of geoneutrino flux in the Western Hemisphere**
- Oscillations averaged to a survival probability of 0.55





Antineutrino Detection

- Antineutrinos **inverse beta decay** on hydrogen nuclei
- Produce **coincidence** of events, powerful for rejecting backgrounds
- Prompt positron energy: $E_{e^+} = E_\nu - 0.8$ MeV
- Delayed neutron capture: $E_\gamma = 2.2$ MeV
- $\Delta T \approx 200\mu$s between prompt and delay events



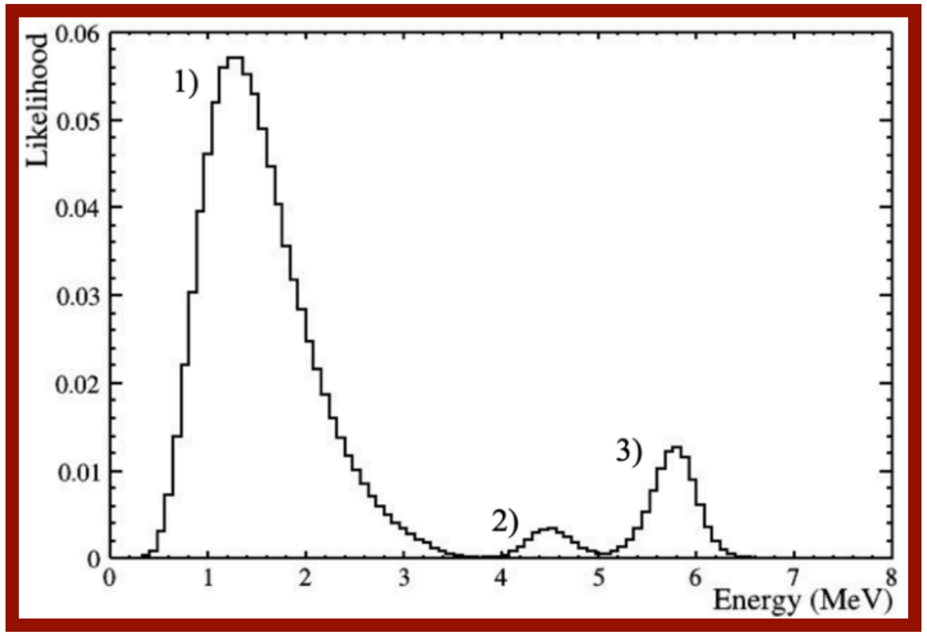
Selection Criteria

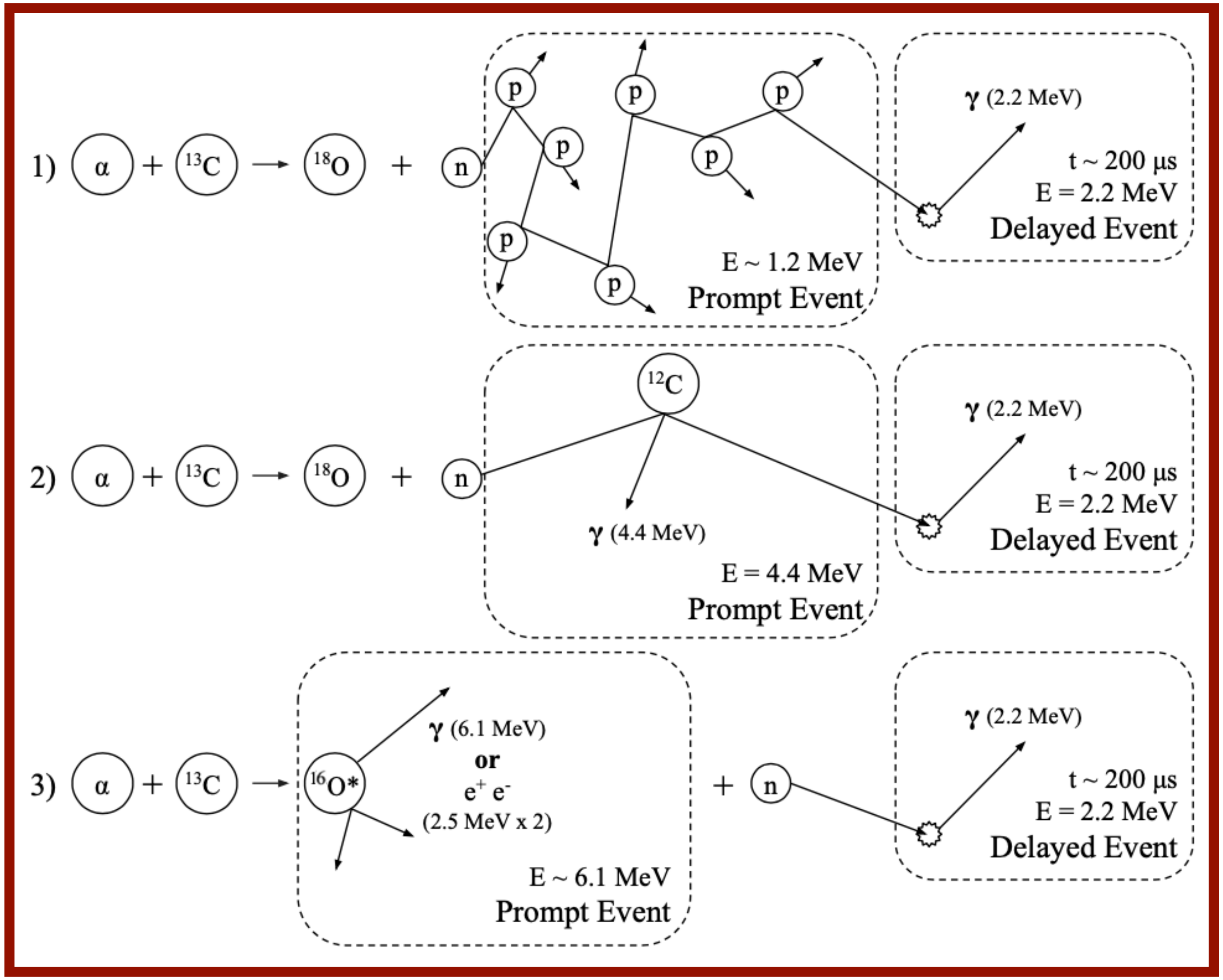
Prompt Energy	0.9 < E < 8.0 MeV
Delay Energy	1.85 < E < 2.5 MeV
Delta T	< 2 ms
Delta R	< 2.5 m

Figure from:
Design and Development of JUNO Event Data Model. Chinese Physics C. 41. 10.1088/1674-1137/41/6/066201.

(α, n) Background

- α particles from ^{210}Po decays in detector medium, capture on ^{13}C inside the detector, **mimicking the IBD coincidence signal**
- Three possible prompt events:
    1. Neutron recoils on protons
    2. Neutron scatters off a ^{12}C
    3. Excited ^{16}O produced which de-excites
- **Main background** to antineutrino IBDs
- ^{210}Po decay rate constantly monitored

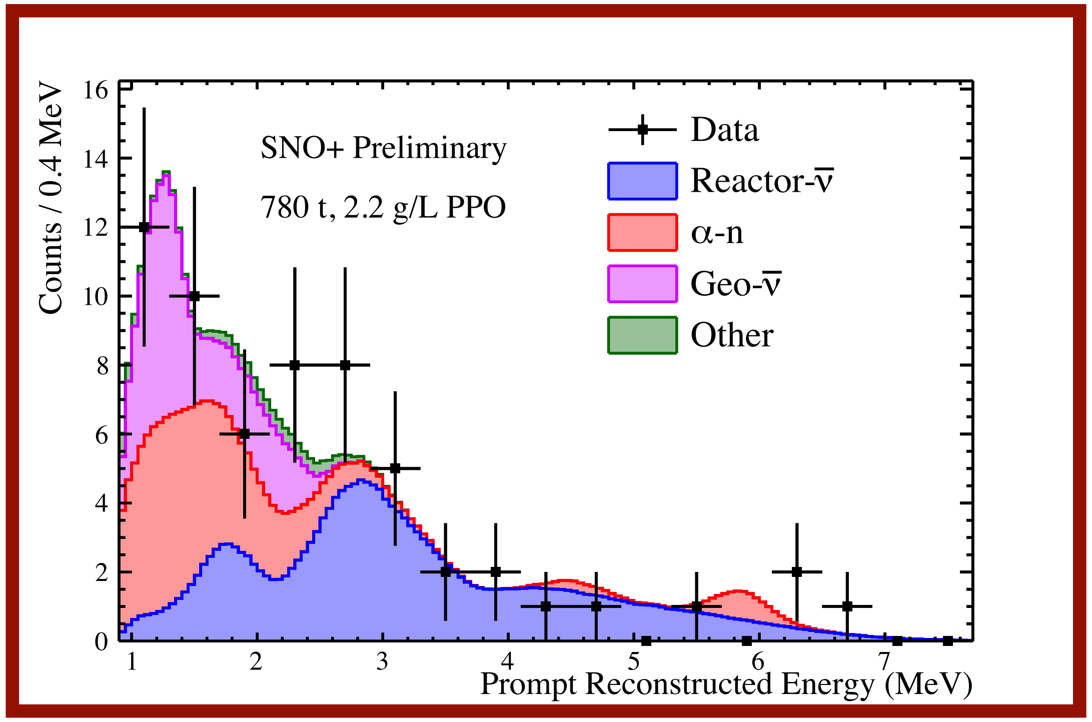


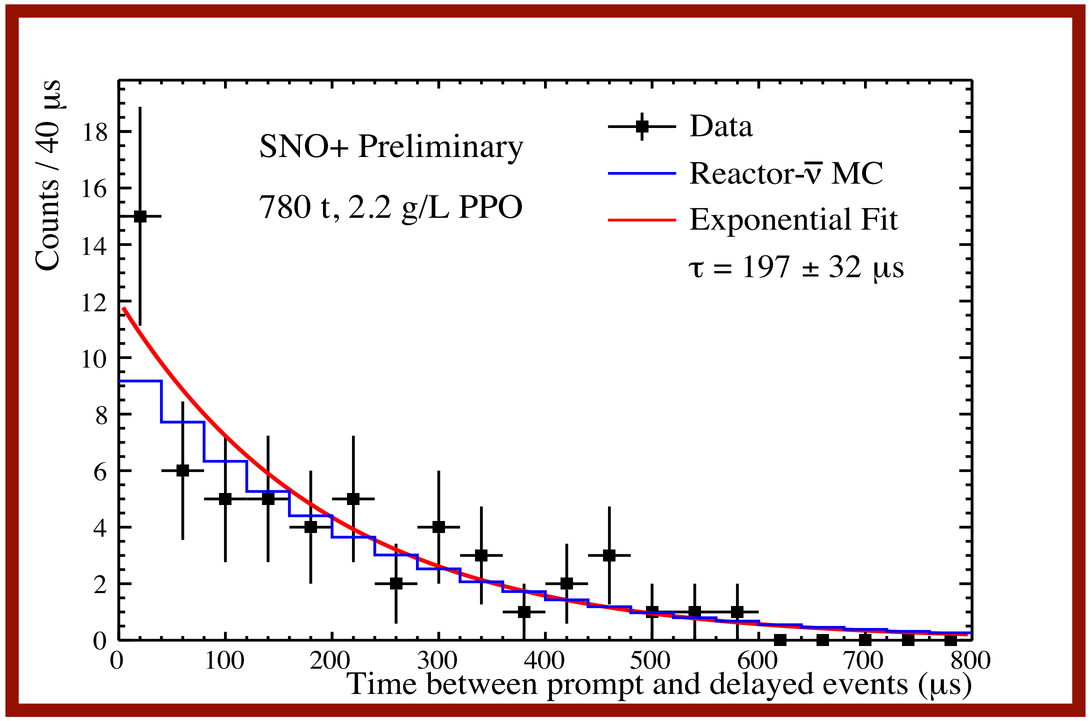


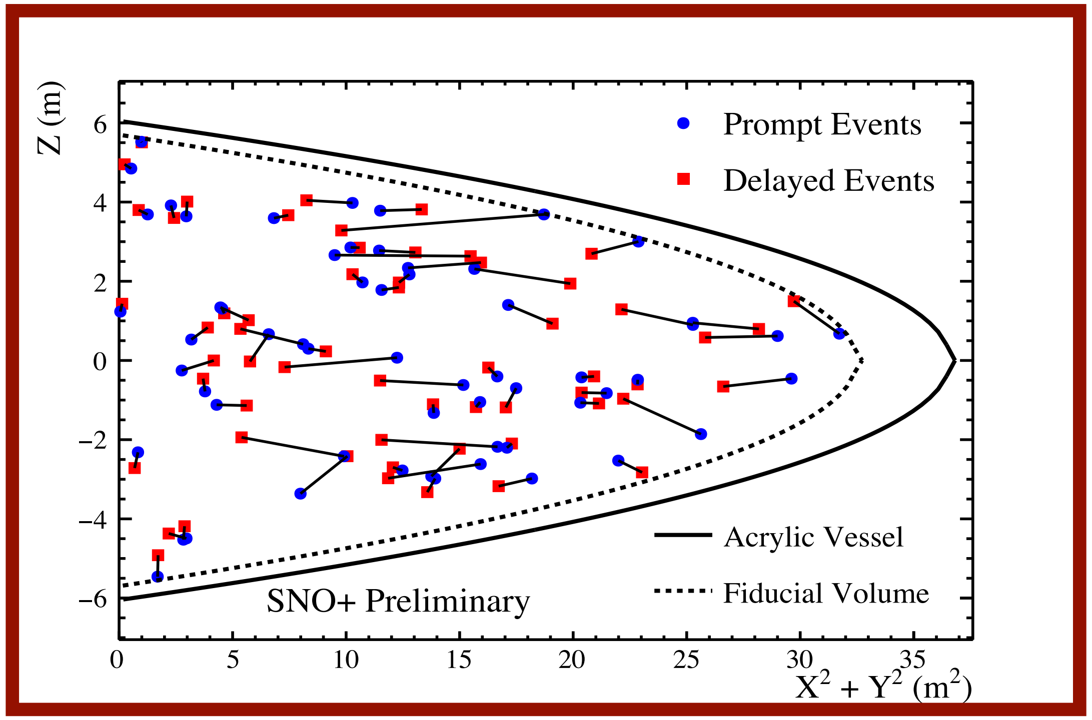
Figures from:
Measurement of Reactor Antineutrino Oscillation with SNO+, A. Zummo, https://repository.upenn.edu/handle/20.500.14332/60242

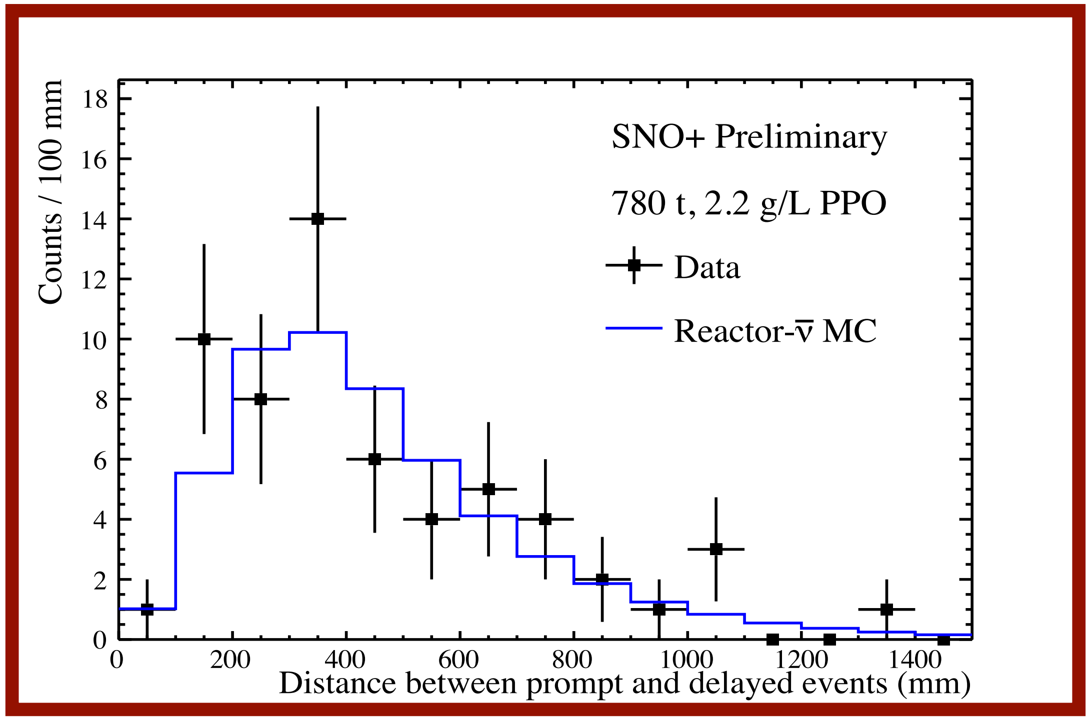
Tagged Events

59 tagged coincidences in **134.5 days** livetime

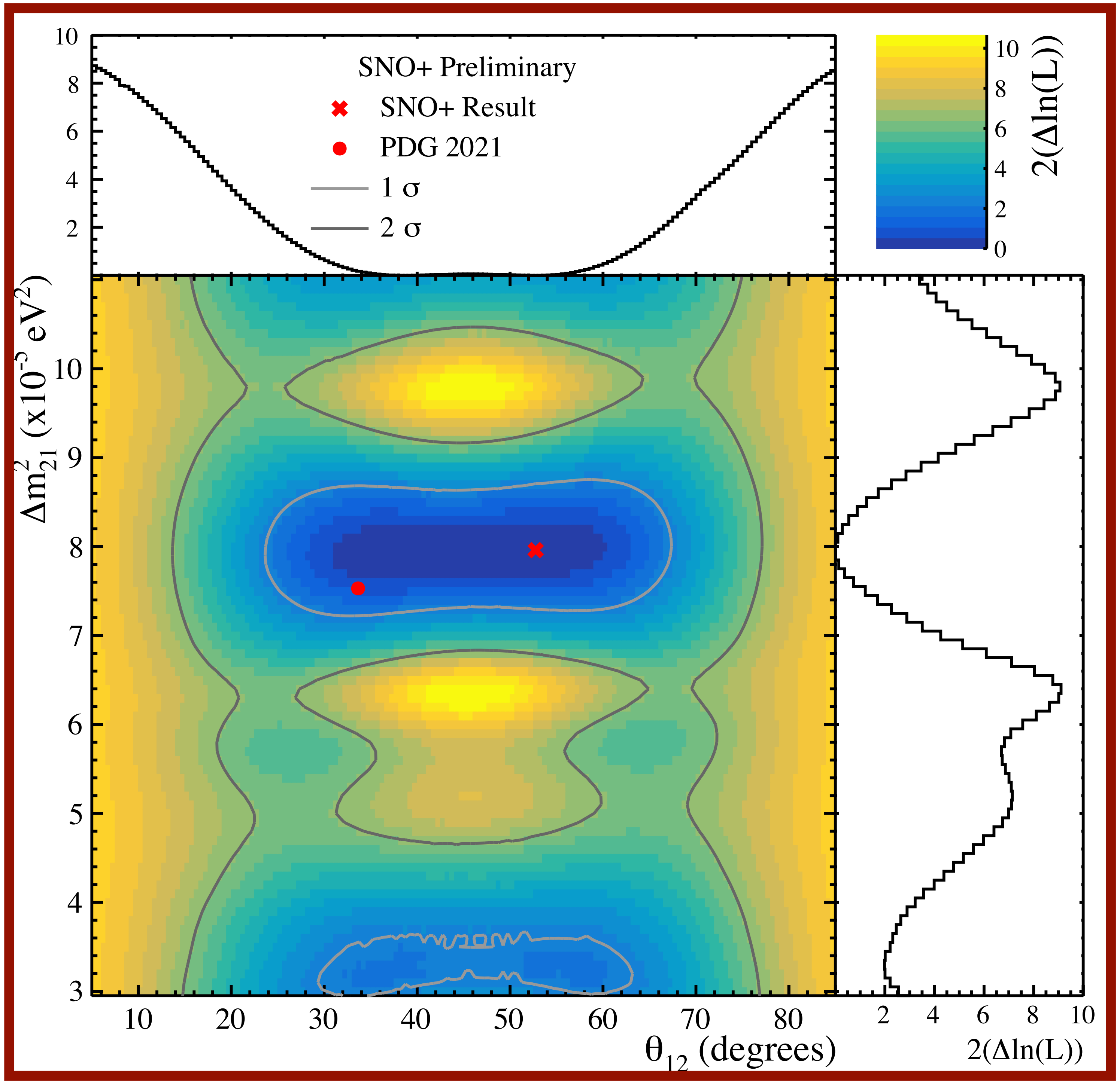








Fit Results



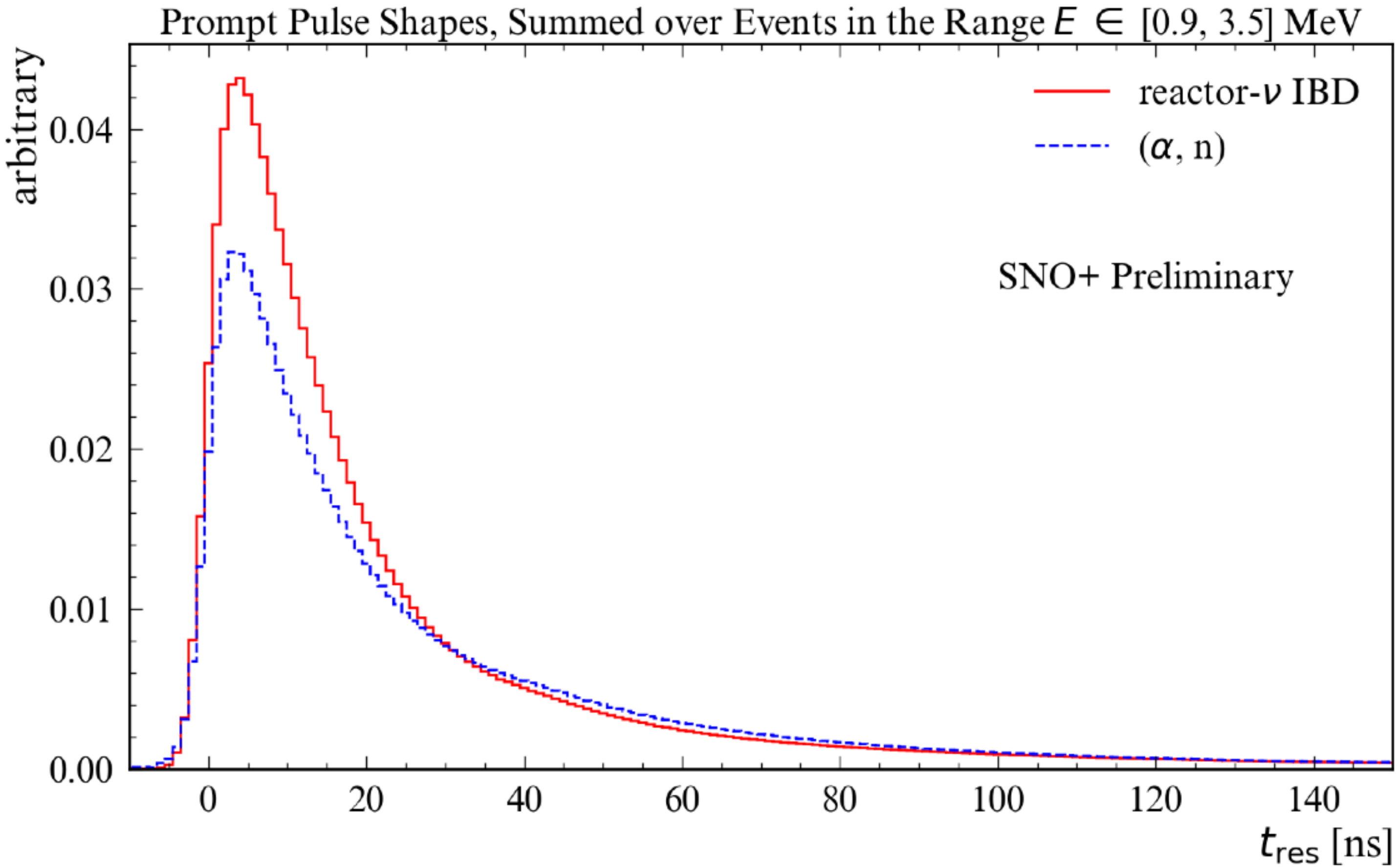
- Fit reactor, geoneutrino, and background PDF normalisations simultaneously with systematics and oscillation parameters
- Plot for unconstrained Δm^2_{21} and θ_{12}
- SNO+ data compatible with global oscillation parameters

	Reactor IBD	**Geoneutrino IBD**	**(α,n)**	**Data**
Fitted Counts	27.5 +/- 0.9	$11.1^{+7.1}_{-6.6}$	$17.2^{+4.5}_{-4.4}$	59
External constraints	+/- 3%	+/- 30% U/Th ratio	30% O 100% O*	

	SNO+ Only	**SNO+ with PDG2021**
$\Delta m^2_{21} (\times 10^{-5} eV^2)$	$7.96^{+0.48}_{-0.42}$	$7.58^{+0.18}_{-0.17}$
$\theta_{12} (^0)$	52^{+10}_{-24}	33.7 ± 0.8
Geoneutrino Flux at SNOLAB (TNU)	73^{+47}_{-43}	64 ± 44

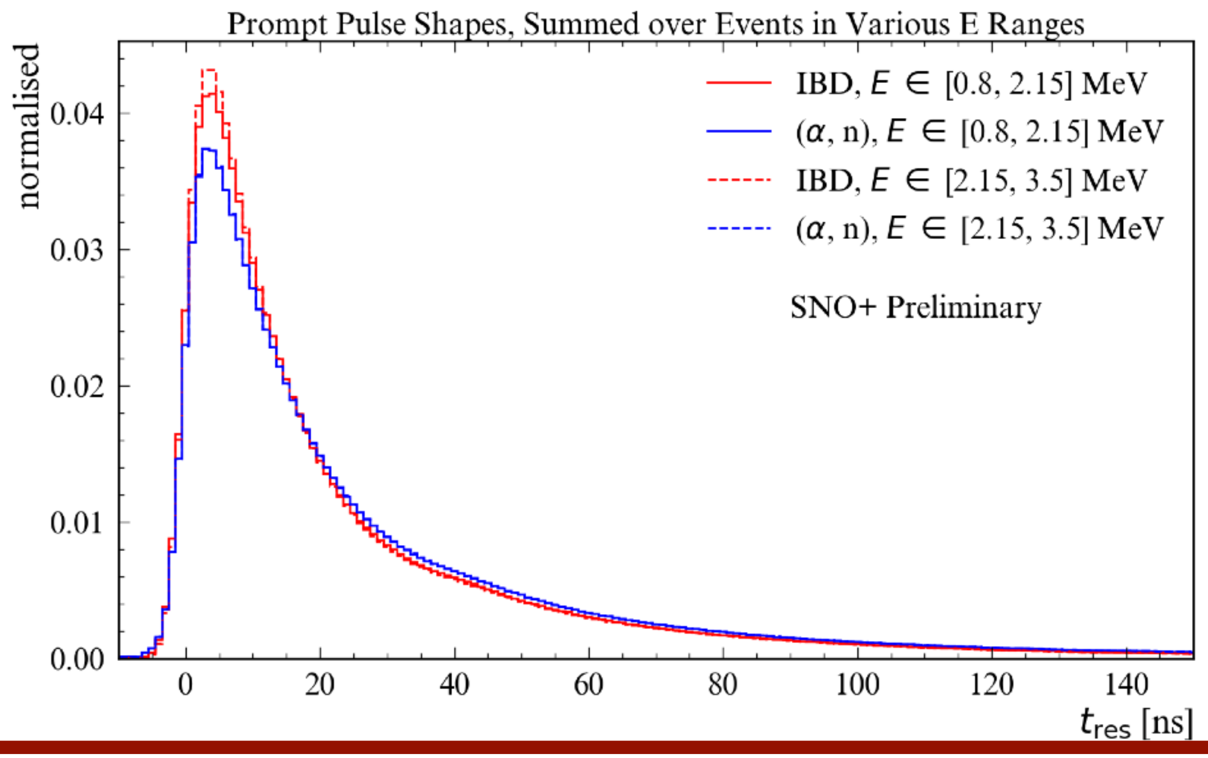
(α, n) Classifier

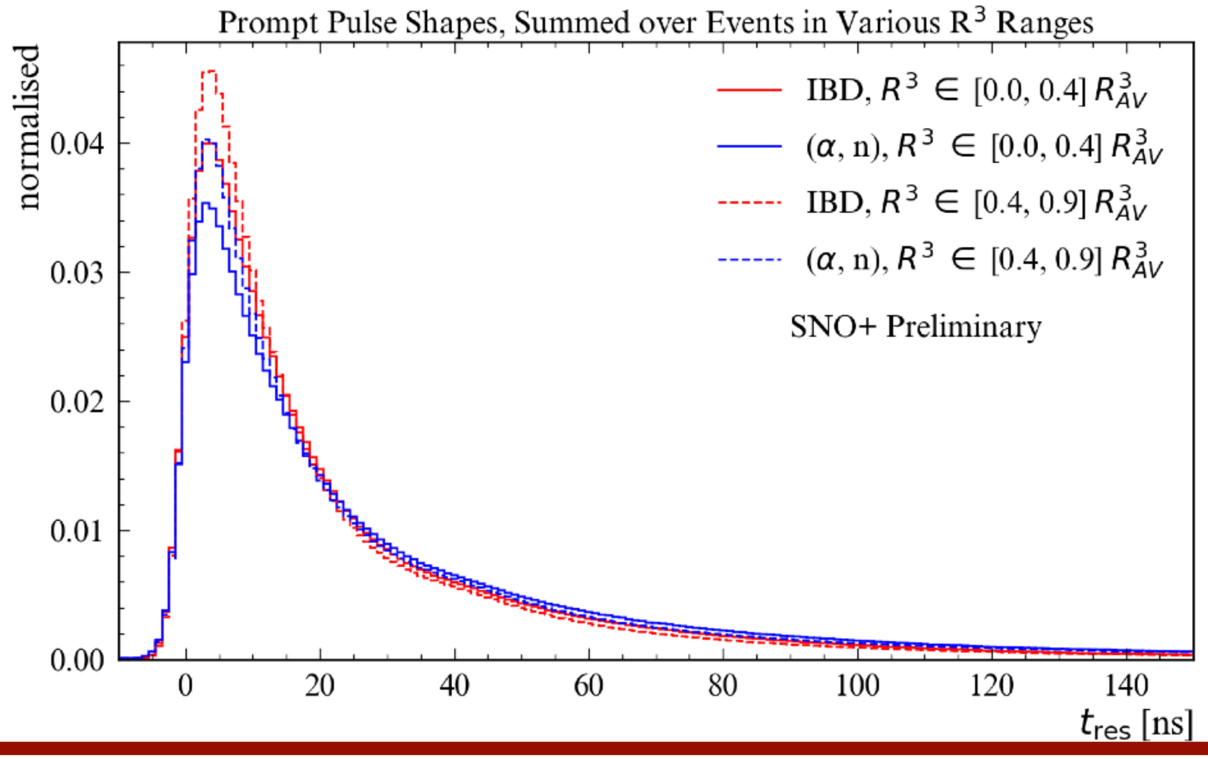
- (α, n) prompt events deposit energy over a slightly longer time than IBD prompt events
- **Scintillation timing** is also different for βs and protons
  - β timing calibrated using in-situ ^{214}Bi and ^{214}Po decay pairs
  - Proton timing to be calibrated with ^{241}Am-^{9}Be source
- Results in a different pulse shape that can be used to distinguish (α, n) from IBD events



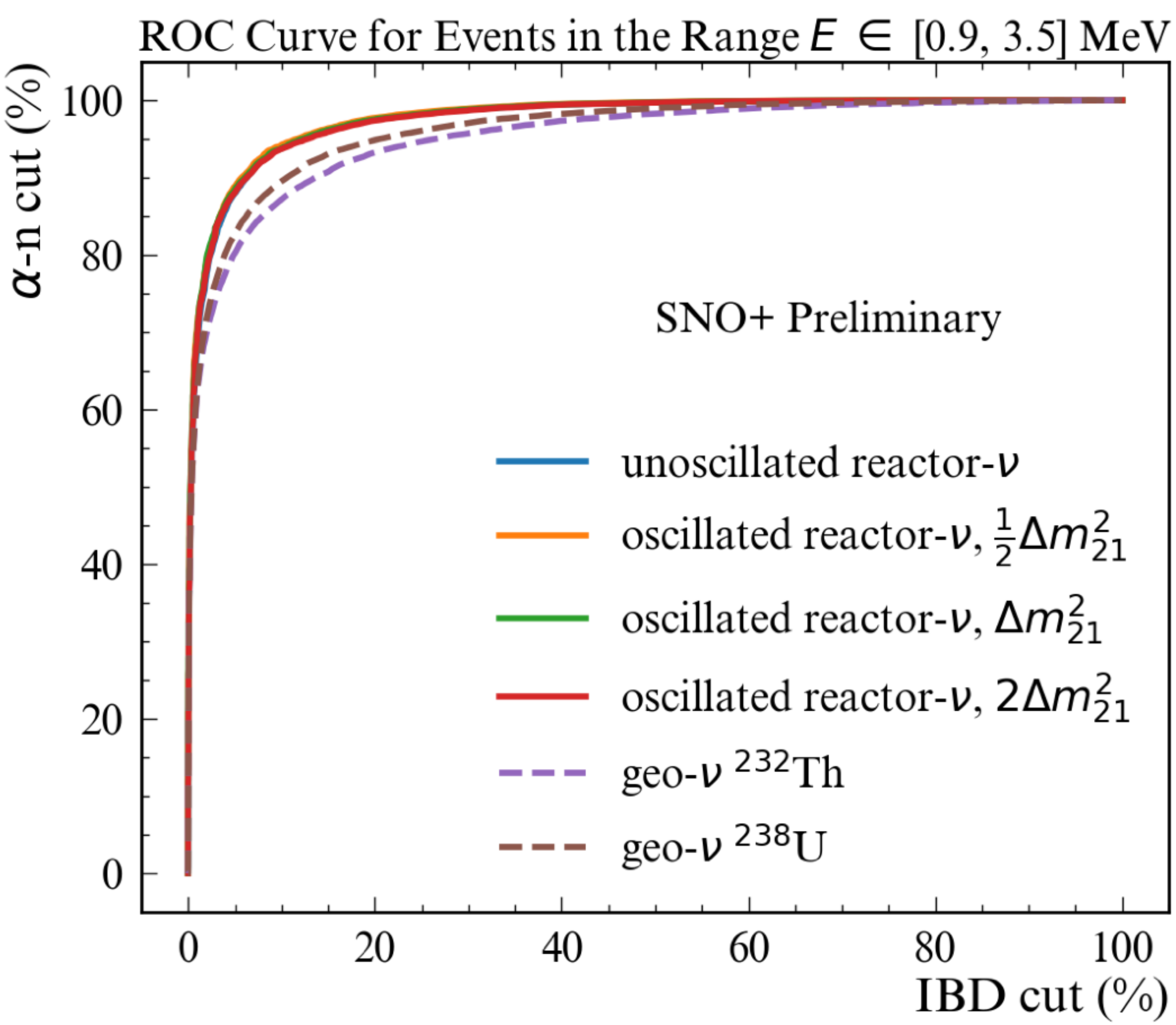
(α, n) Classifier

- Pulse shapes also correlated with **energy** and **radial position**, in different ways for βs and protons
- Likelihood ratio would not capture this with PDFs averaged over E and R
- Instead use **Fisher Discriminant**
  - Finds projection vector that best separates (α, n) from IBDs
- Tune on (α, n) and IBD simulation





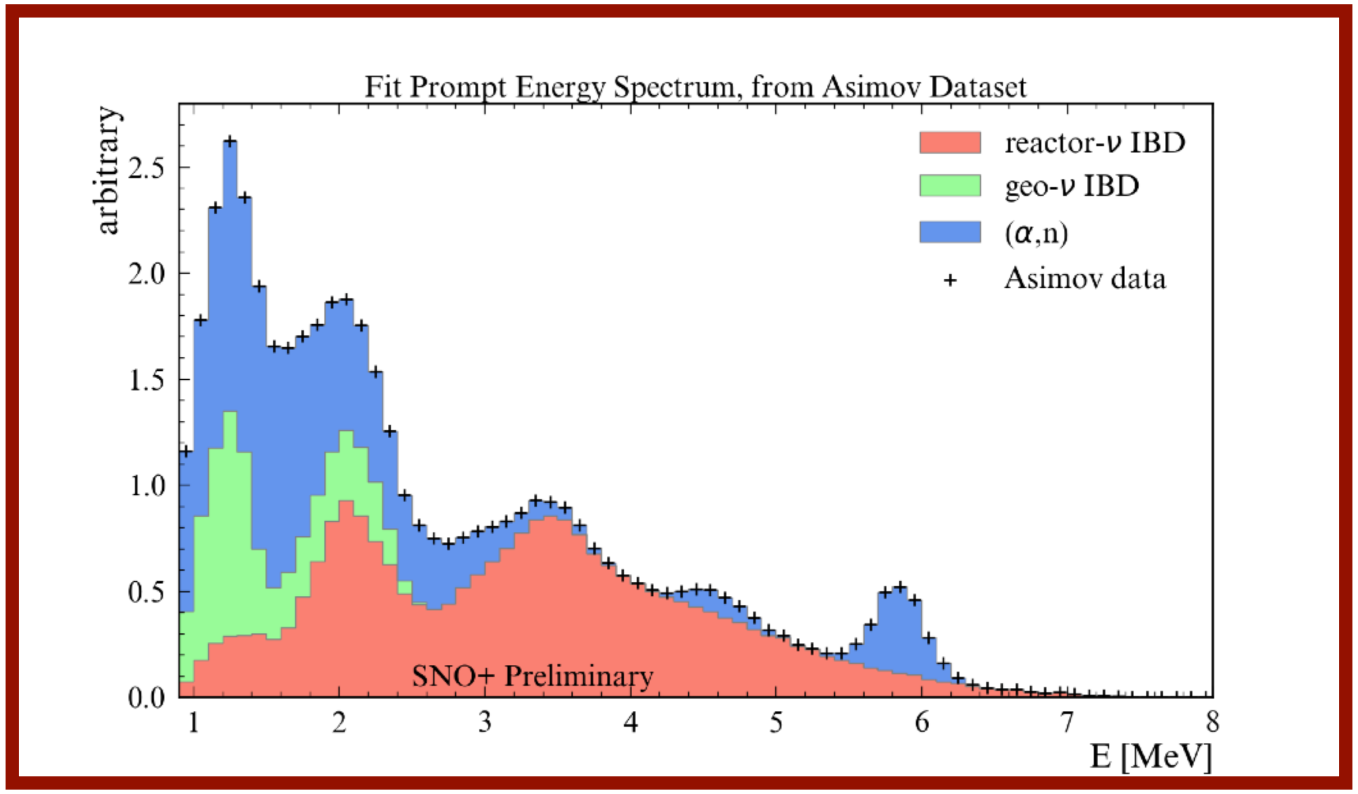
(α, n) Classifier



- Cuts out **90%** of (α, n), sacrifices **11%** geoneutrinos, **6%** reactor antineutrinos
- Performance independent of oscillation parameters

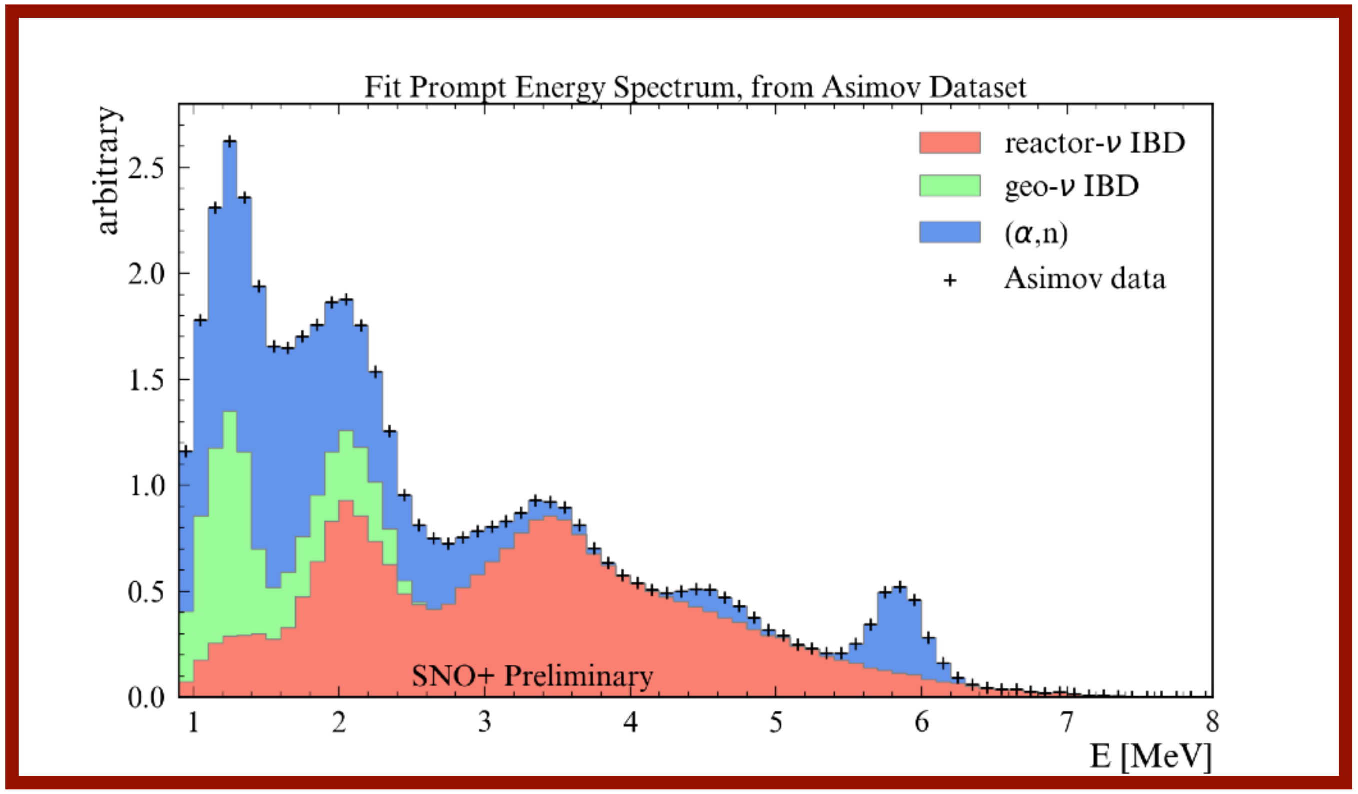
(α, n) Classifier

Pre-Classifier

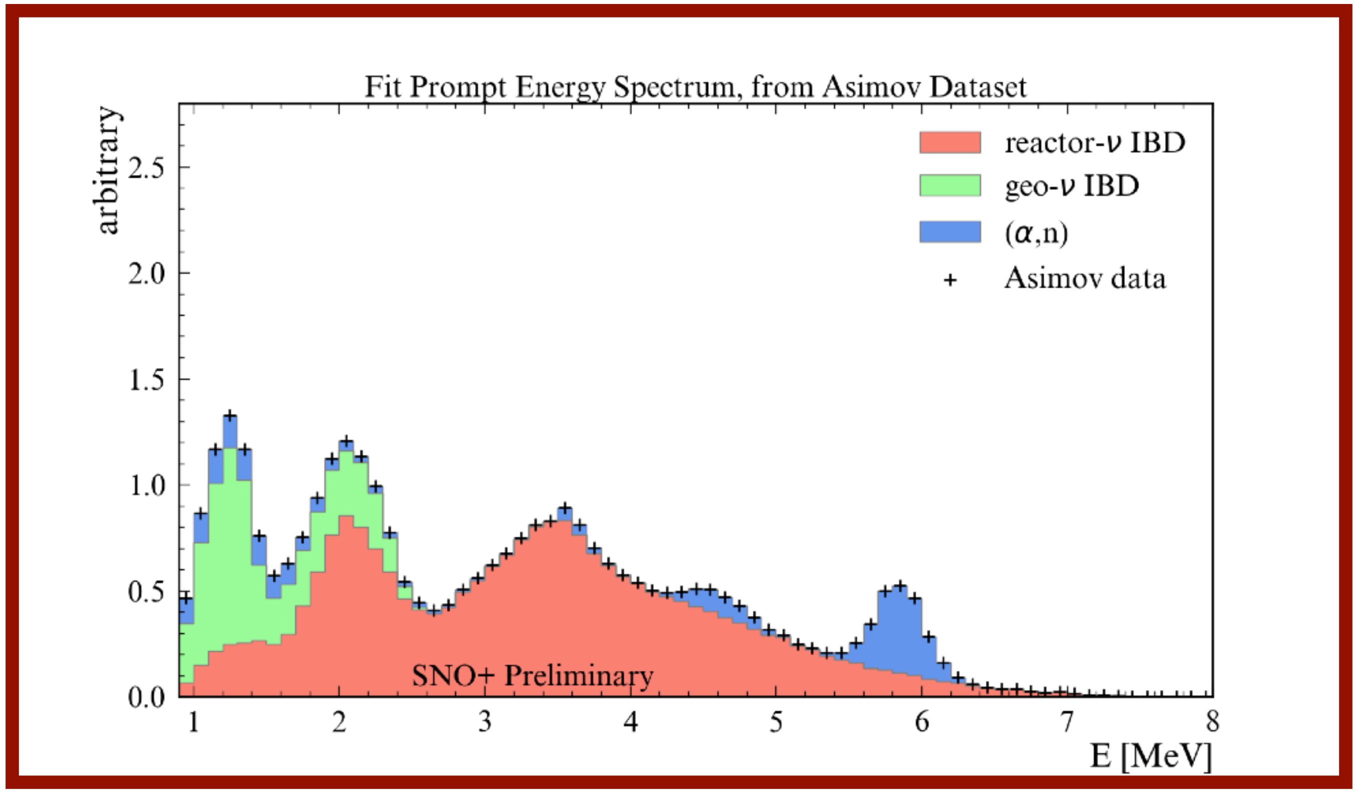


(α, n) Classifier

Pre-Classifier

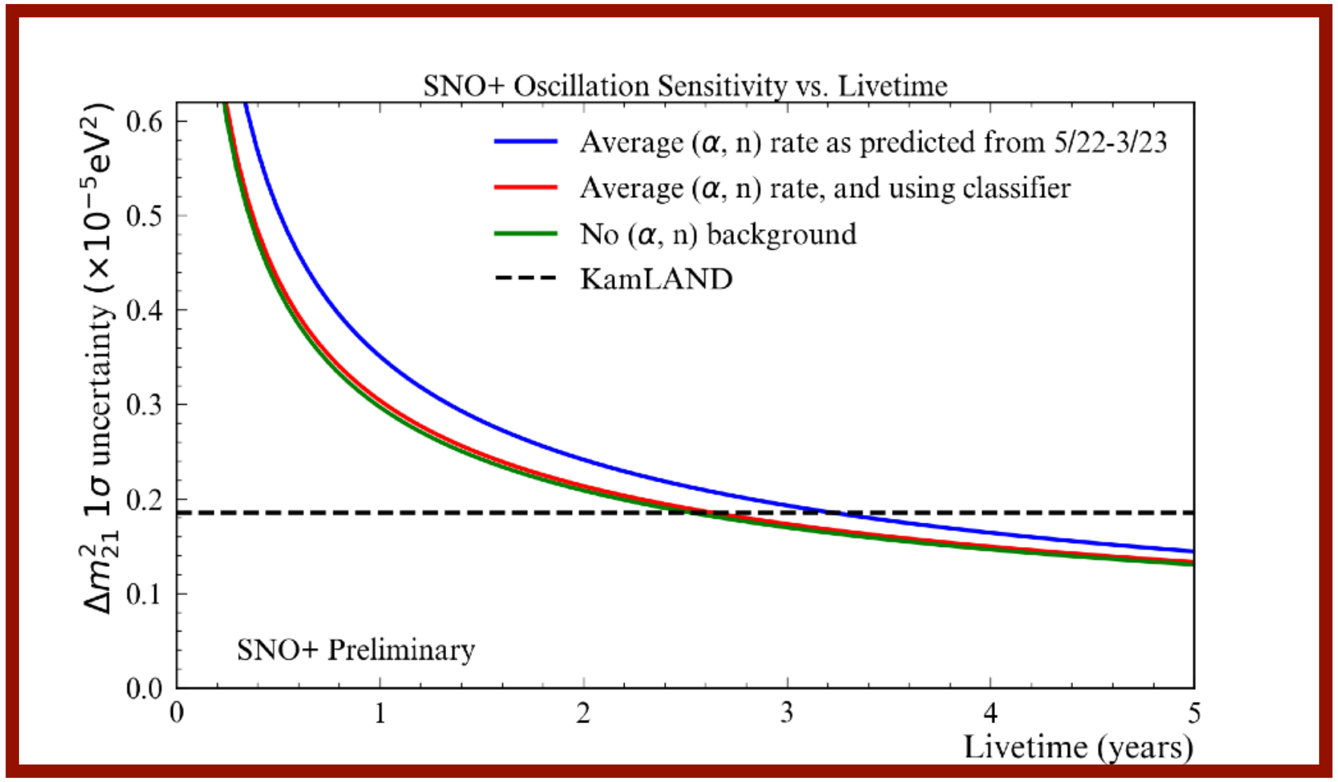


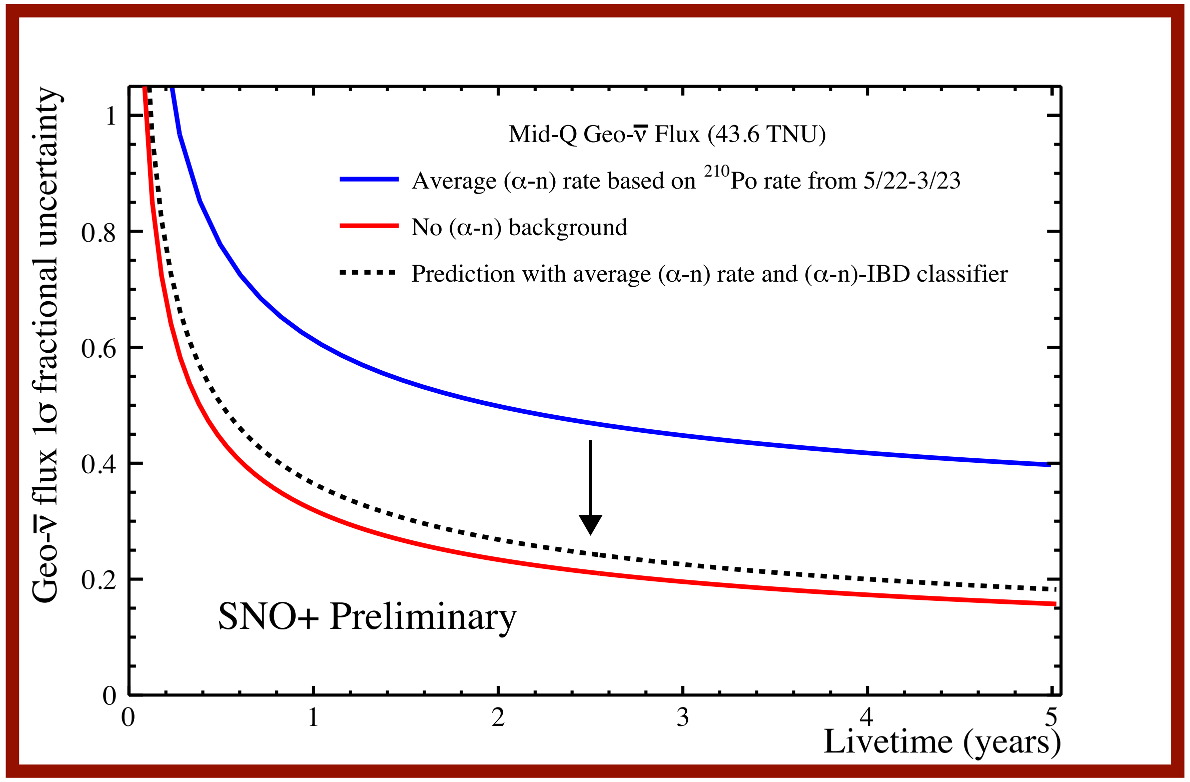
With Classifier



Future Prospects

- In **3 years**, SNO+ is expected to match KamLAND precision on Δm^2_{21}, driven largely by classifying (α, n) events
- (α, n) classifier **drastically reduces impact** of (α, n) events on Geoneutrino flux measurement
- Δm^2_{21} measurement also significantly improved by (α, n) classifier





Summary

- SNO+ is filled with liquid scintillator and taking physics data
- Measured $\Delta m^2_{21} = 7.58^{+0.18}_{-0.17} \times 10^{-5}$ eV^2, $\theta_{12} = 33.7 \pm 0.8^{\circ}$,

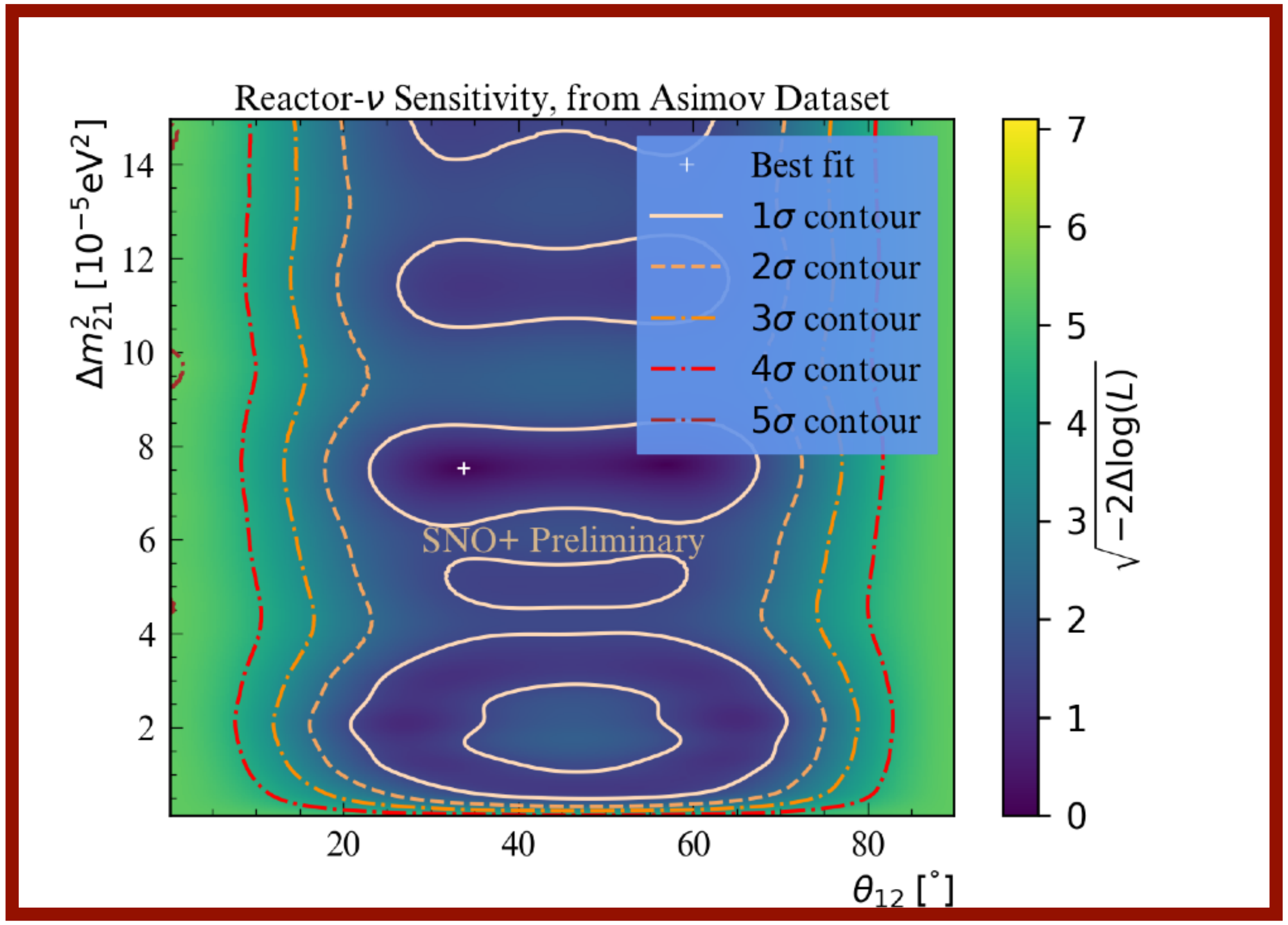
  Geoneutrino Flux $= 64 \pm 44$ TNU, using PDG prior constraints
  - **Second measurement of Δm^2_{21} from reactor antineutrinos**
  - **First measurement of geoneutrino flux in North America**
- Precision will improve with more data!
  - In **3 years**, SNO+ is expected to match KamLAND precision on Δm^2_{21}
  - Antineutrino analyses will continue through the tellurium phase


SNO+, 2024

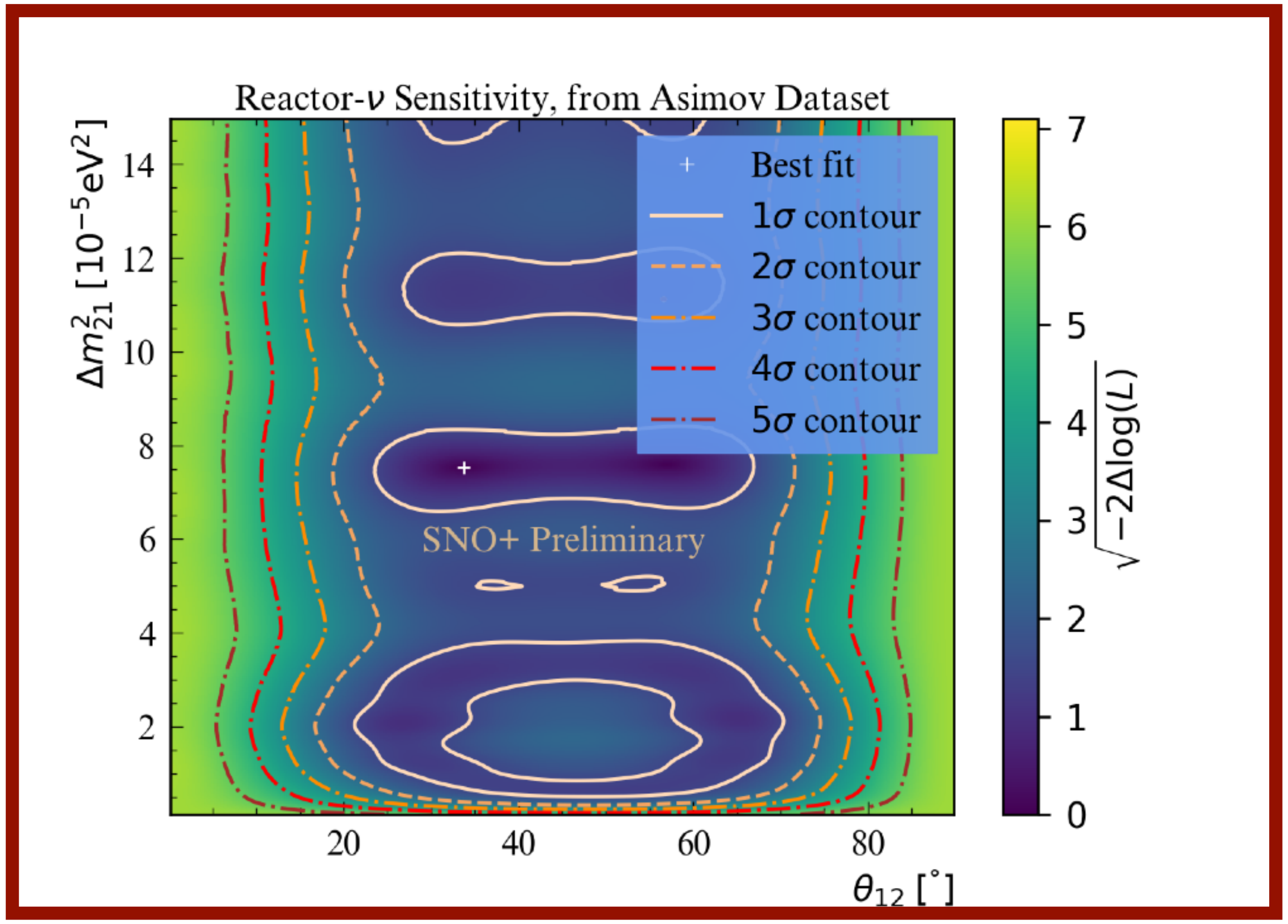
Backups

(α, n) Classifier: Asimov Fits

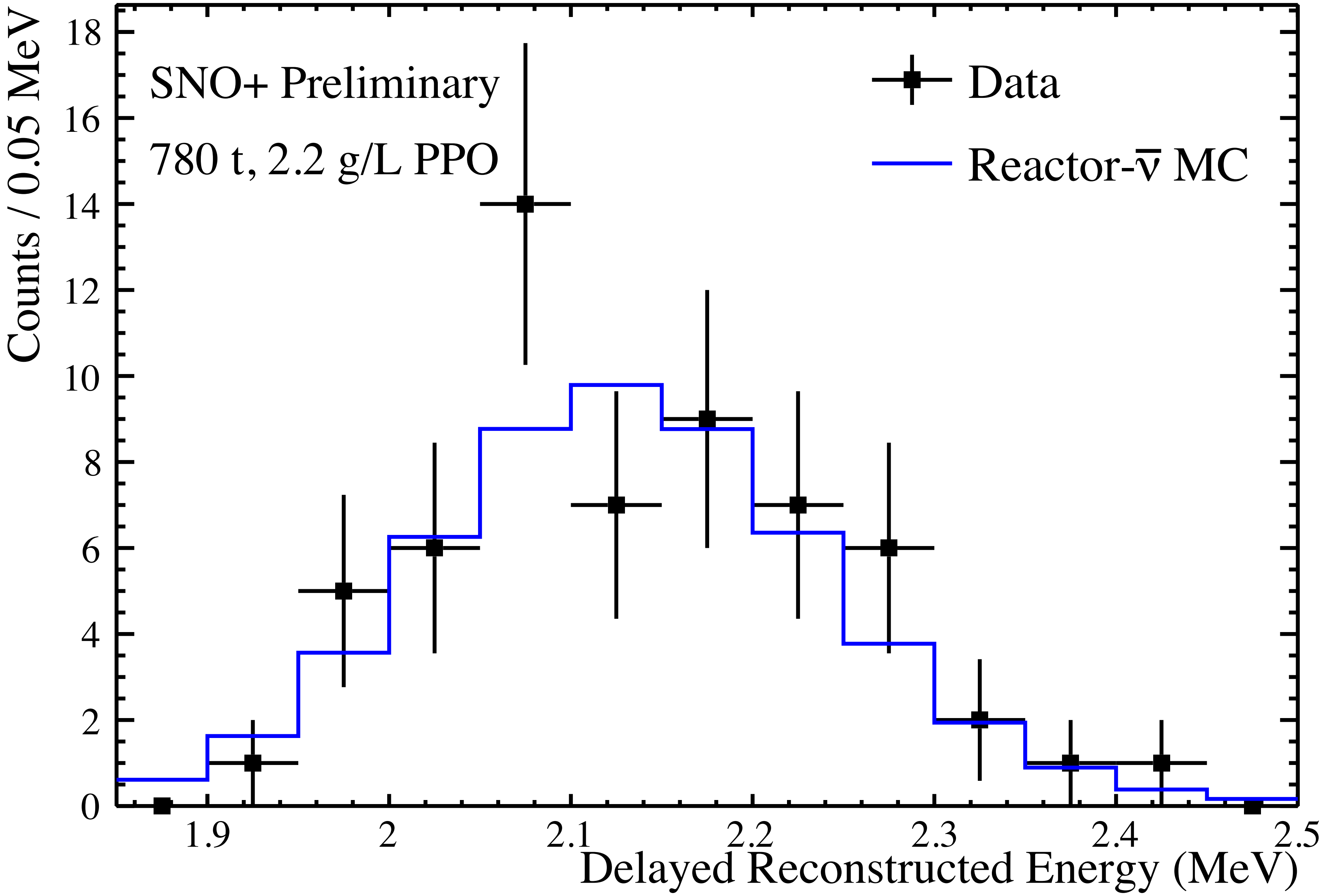
Pre-Classifier



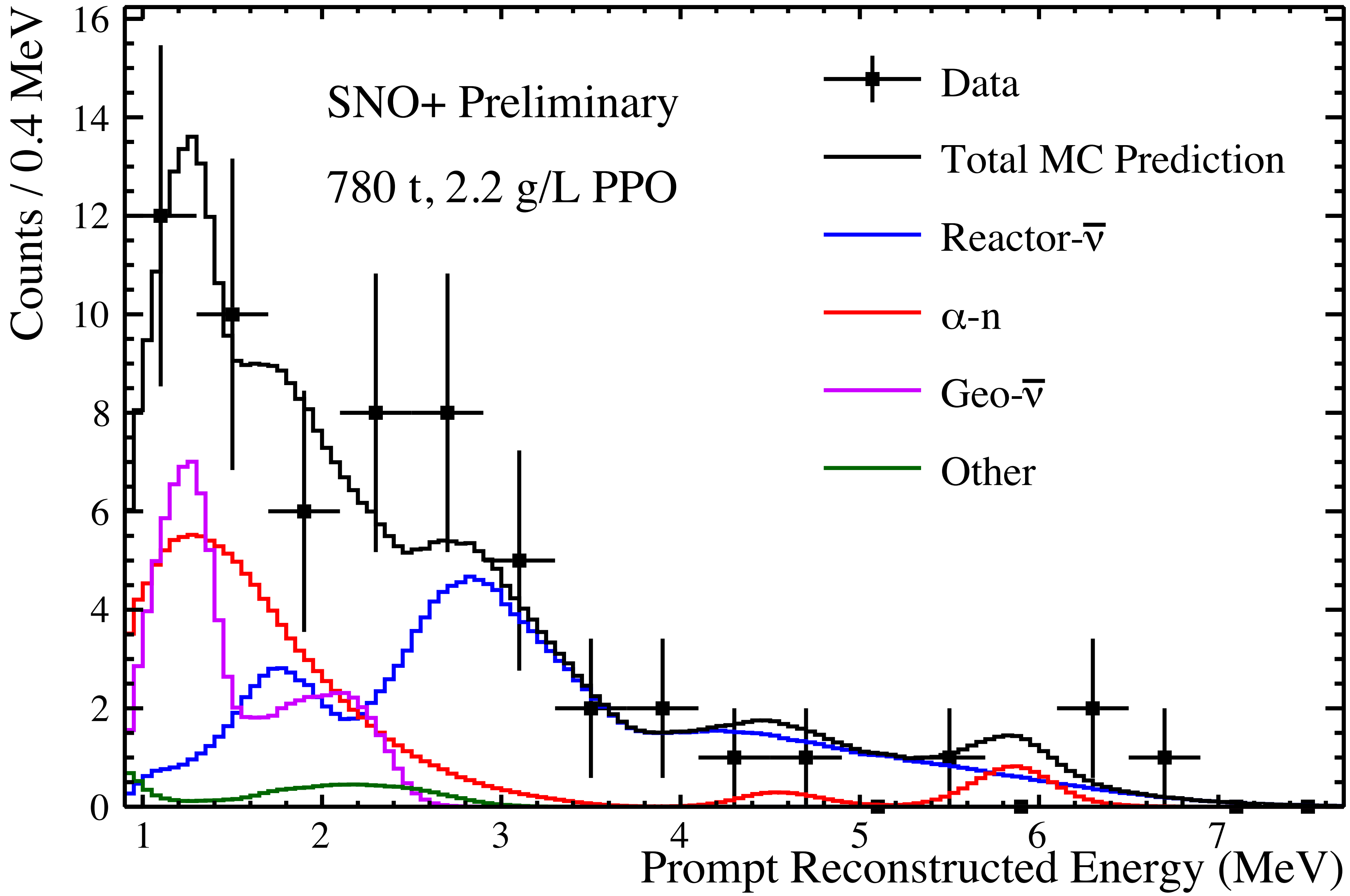
With Classifier



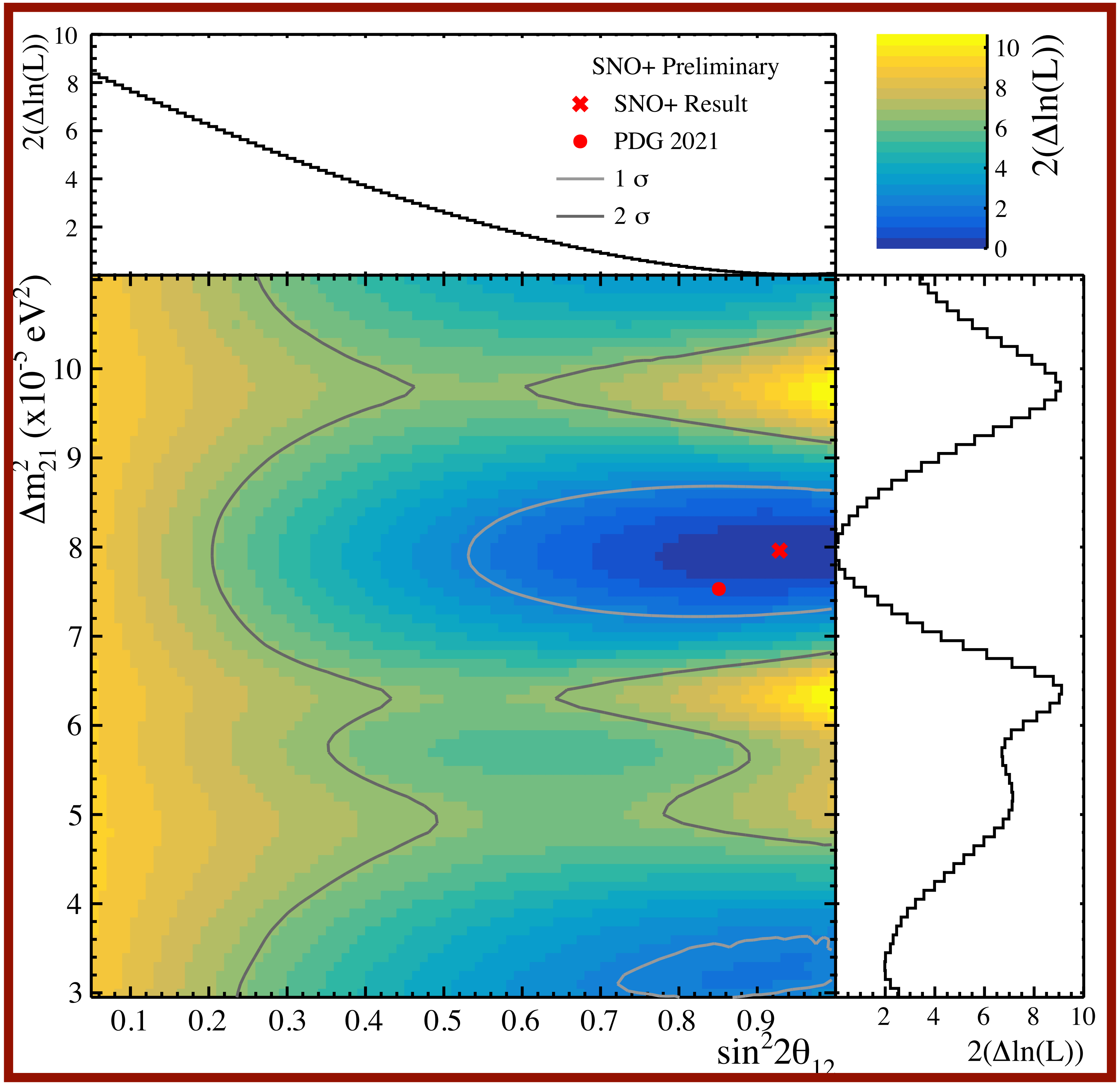
Delay Energy Spectrum



Prompt Energy Spectrum

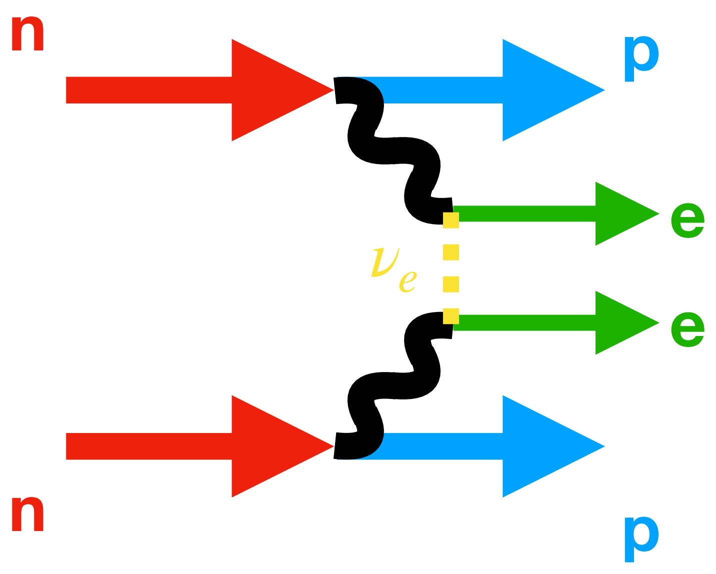


Sensitivity in $\sin^2(2\theta_{12})$

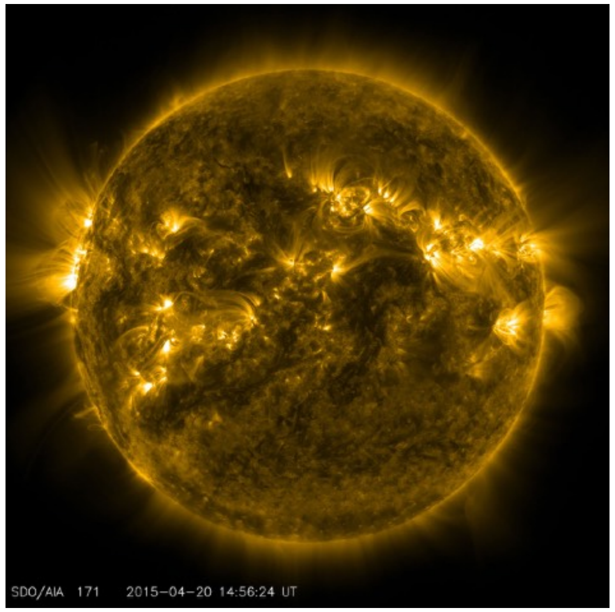


Physics Program

Search for $0\nu\beta\beta$ in ^{130}Te

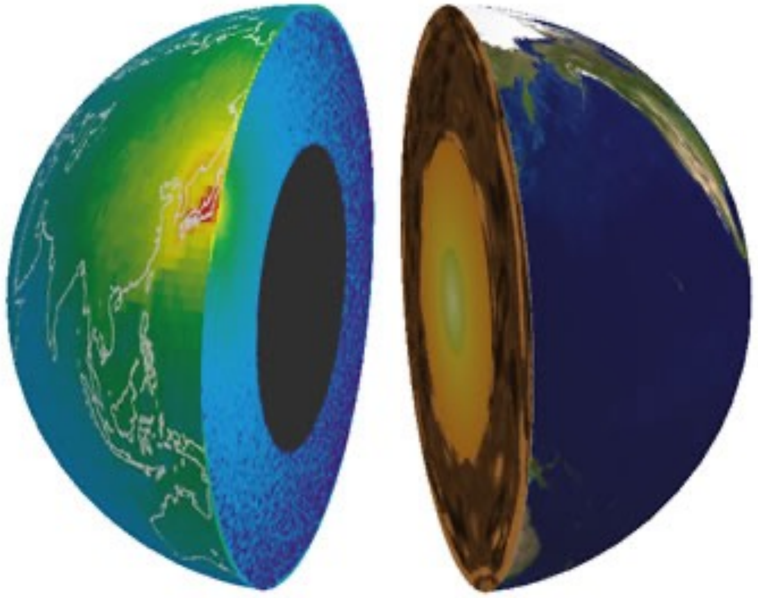


Solar Neutrinos



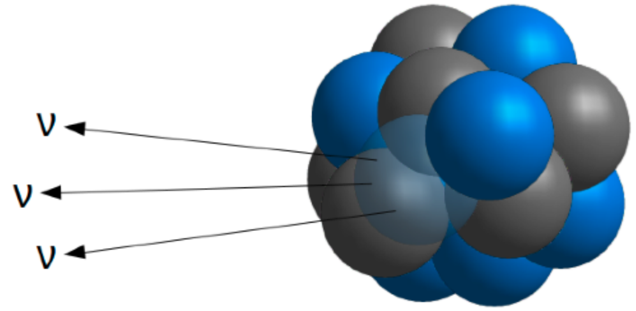
Reactor Anti-Neutrinos

Geo-Neutrinos

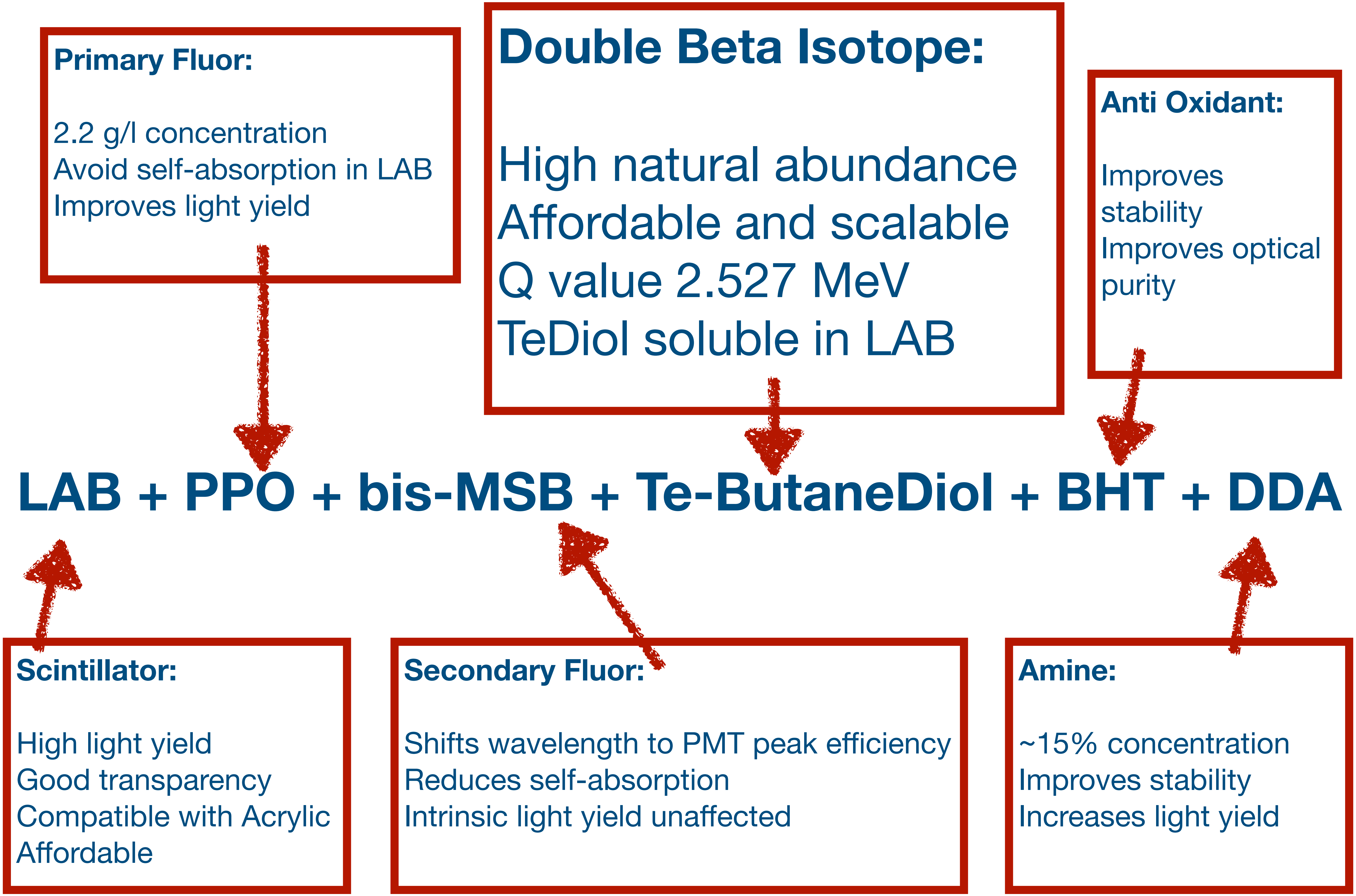


Supernova Neutrinos

Invisible Nucleon Decay



SNO+ Liquid Scintillator Cocktail



Primary Fluor:

2.2 g/l concentration
Avoid self-absorption in LAB
Improves light yield

Double Beta Isotope:

High natural abundance
Affordable and scalable
Q value 2.527 MeV
TeDiol soluble in LAB

Anti Oxidant:

Improves stability
Improves optical purity

LAB + PPO + bis-MSB + Te-ButaneDiol + BHT + DDA

Scintillator:

High light yield
Good transparency
Compatible with Acrylic
Affordable

Secondary Fluor:

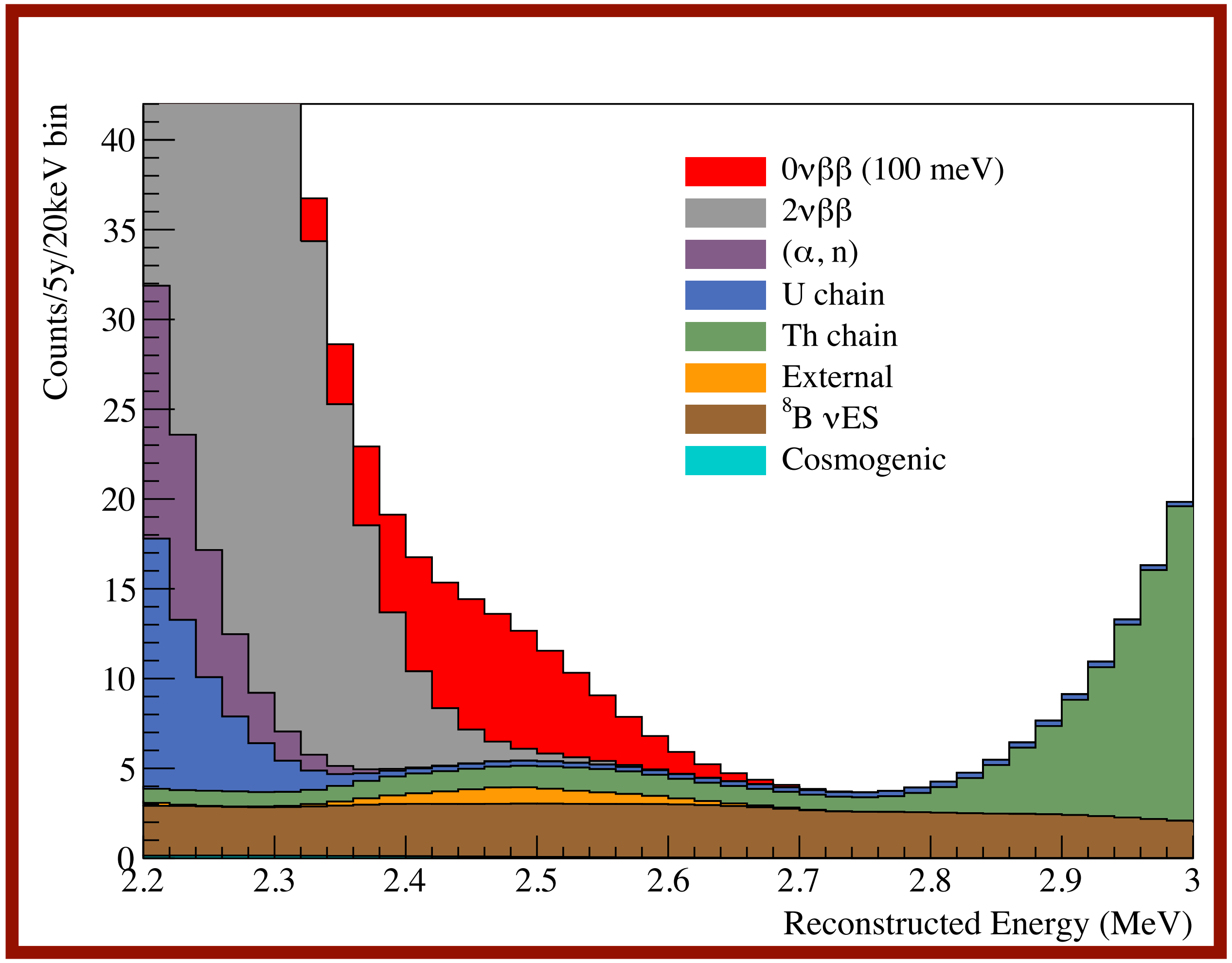
Shifts wavelength to PMT peak efficiency
Reduces self-absorption
Intrinsic light yield unaffected

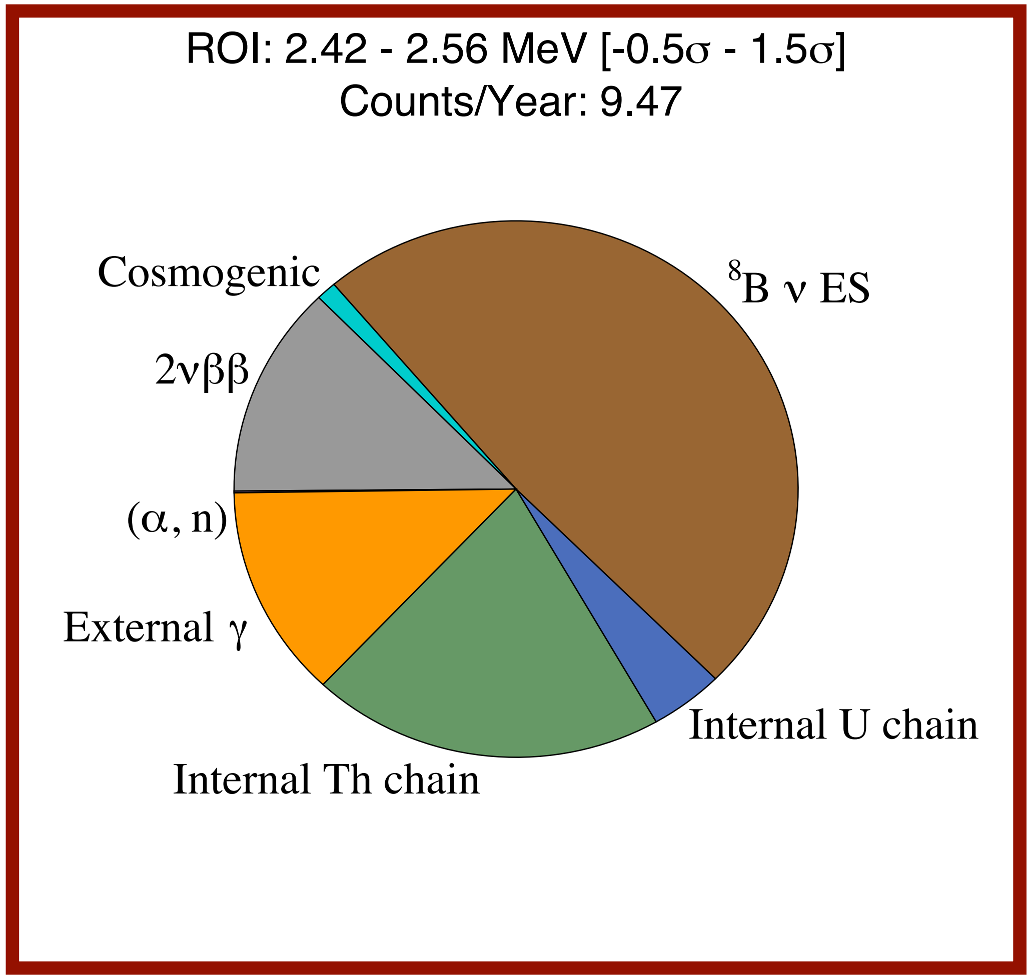
Amine:

~15% concentration
Improves stability
Increases light yield

$0\nu\beta\beta$ Analyses

All backgrounds on target for world leading $0\nu\beta\beta$ sensitivity





SNO+ $0\nu\beta\beta$ Future Sensitivities

- SNO+ scalable with higher loading of Te
  - Stable and high light yield at several percent loading
  - Cost relatively low (<$2m per ton)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \langle m_{\beta\beta}\rangle^2 \times |M_{0\nu}|^2 \times G_{0\nu}$$

$$\langle m_{\beta\beta}\rangle = \left| \sum_i m_i U_{ei}^2 \right|$$