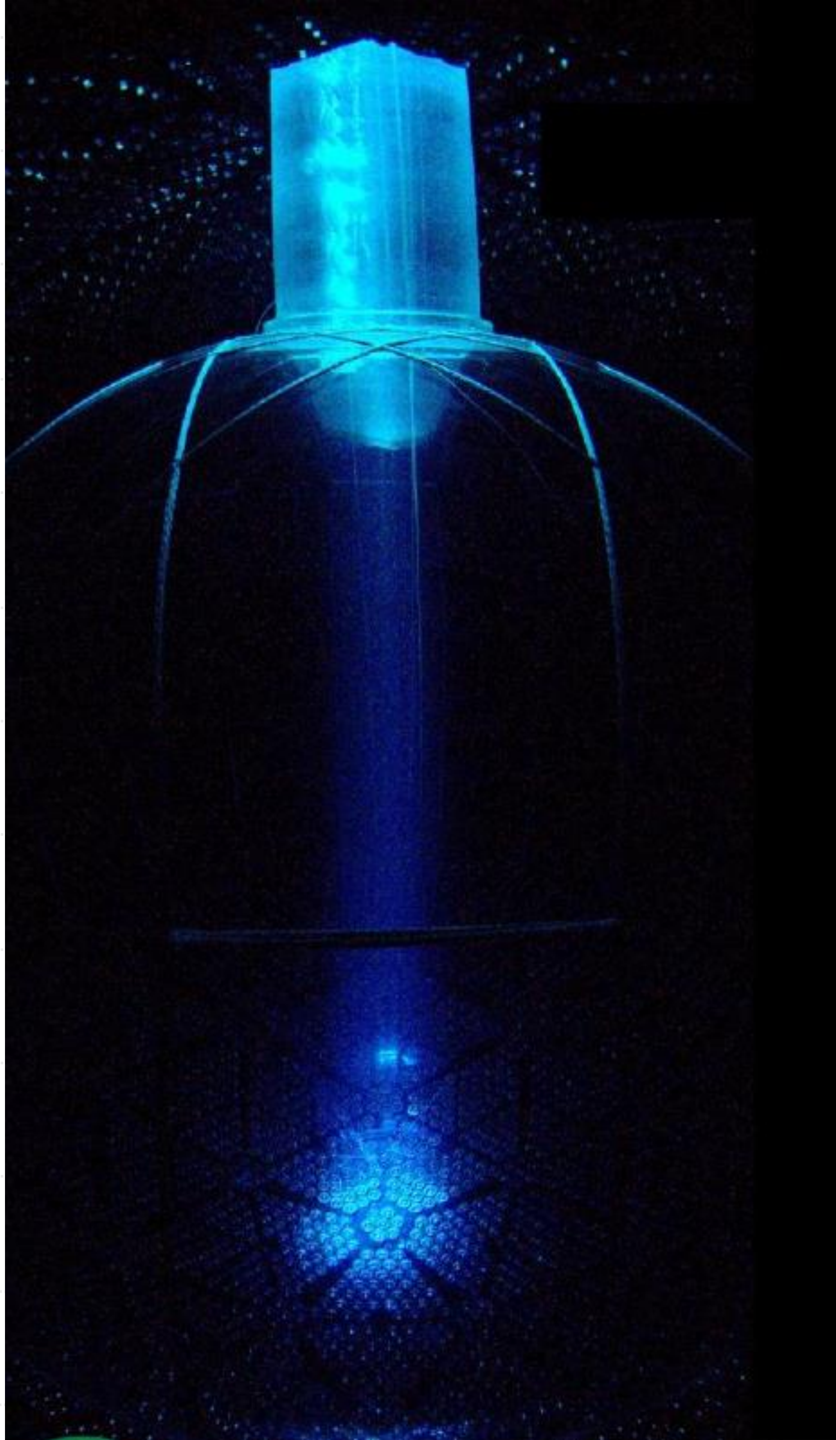
Queen's University

Measurement of Reactor Antineutrino Oscillation at SNO+

James Page,
on behalf of the SNO+ collaboration

2026 CAP Congress, Ottawa



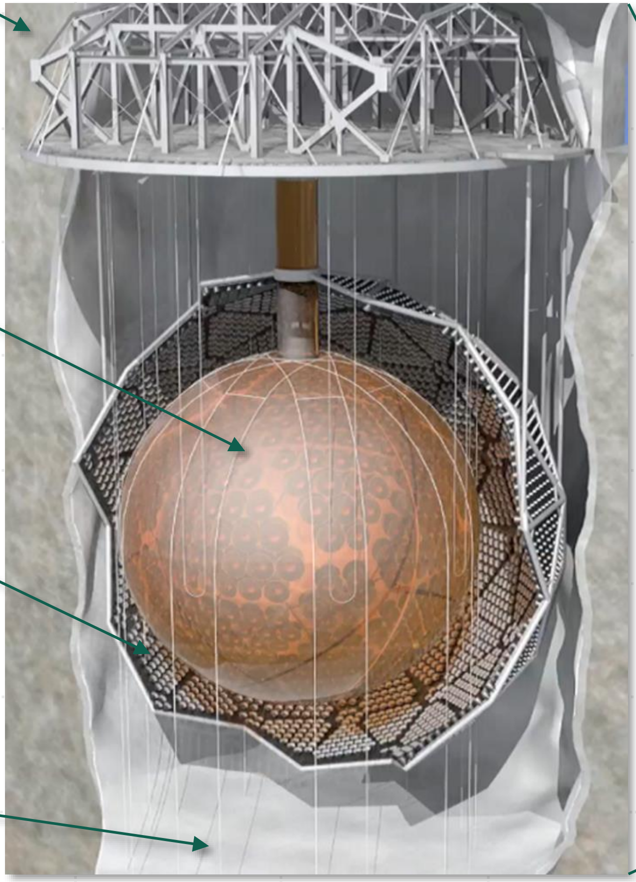
The SNO+ Detector

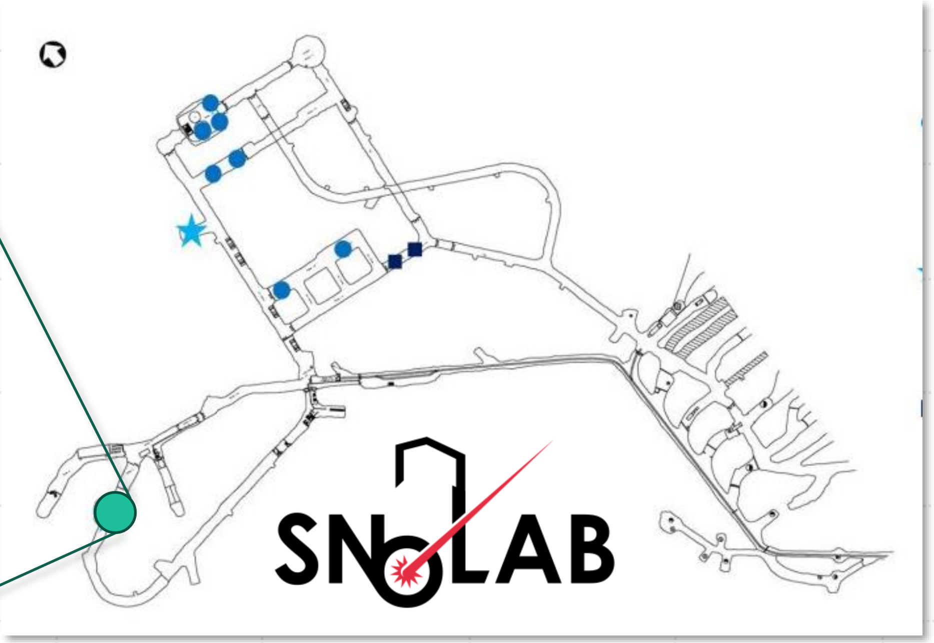
2 km overburden

6 m radius acrylic vessel (AV) filled with liquid scintillator

Over 9000 PMTs + outward looking PMTs

Surrounded by ultra-pure water





SNO+ Timeline

Water Phase

2017-2019

905 t ultra-pure water

Detector calibration
External background measurements

"Partial-fill" Phase

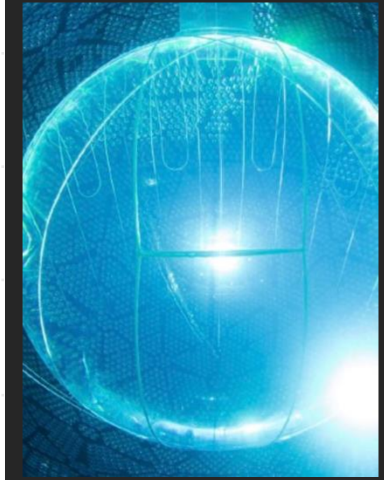
2019-2022

Half replaced with liquid scintillator (COVID19 pause)

LAB + 0.6 g/L PPO

Scintillator Phase

2022-ongoing



Completed loading of 780 t liquid scintillator

Initial: LAB + 2.2g/L PPO
Enhanced (2023-onwards): LAB + 2.2g/L PPO + 2.2 mg/L bis-MSB

Tellurium Phase

Search for $0\nu\beta\beta$

Neutrino Publications

Water phase:

- Measurement of the ^{8}B solar neutrino flux using the full SNO+ water phase dataset
- Evidence of Antineutrinos from distant reactors using pure water at SNO+

Partial-fill:

- Event-by-event direction reconstruction of solar neutrinos in a high light-yield liquid scintillator
- Initial measurement of reactor antineutrino oscillation at SNO+

Scintillator phase:

- First evidence of solar neutrino interactions on ^{13}C
- Measurement of reactor antineutrino oscillation at SNO+ (0.29 ktonne-years)
- Preprint: Measurement of reactor antineutrino oscillations with 1.46 ktonne-years of data at SNO+

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Neutrino Oscillation

- Neutrino flavour and mass states mis-matched (PMNS matrix):

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U^* \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij}$$

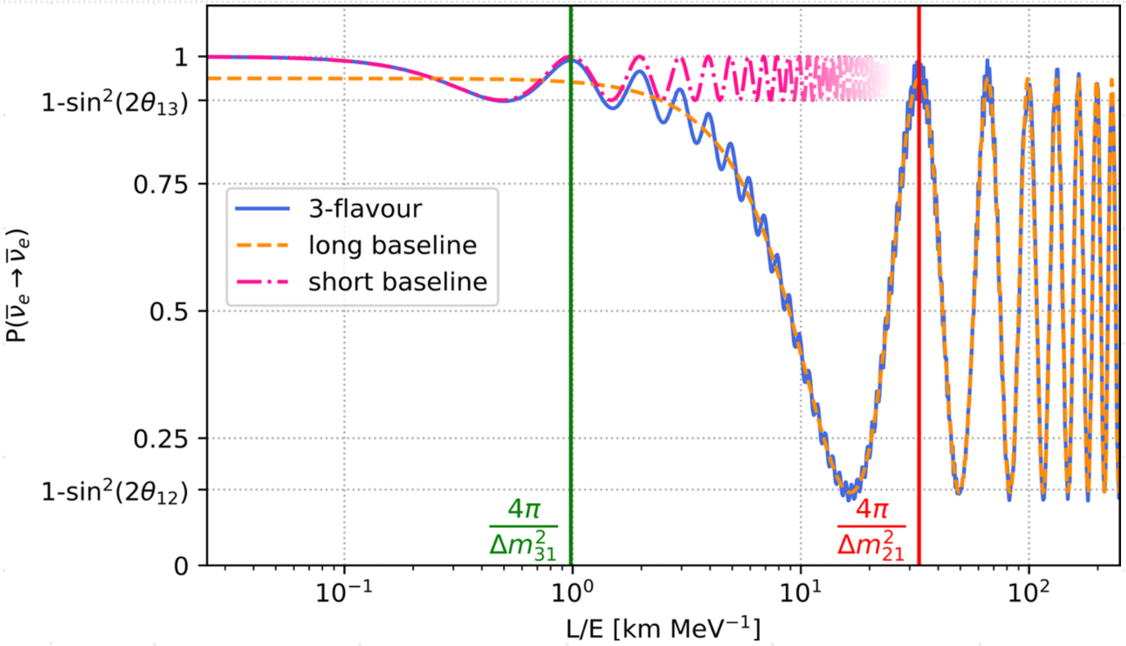
- For ultra-relativistic plane waves, the **transition probability**:

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

Neutrino Oscillation

Example: (anti)neutrino survival probability



Oscillation effectively decouples into two ranges:

- Short baseline (Δm^2_{31}, θ_{13}).
- Long baseline (Δm^2_{21}, θ_{12}).

$\frac{4\pi}{\Delta m^2_{31}} \approx 1\ \mathrm{km} \cdot \mathrm{MeV}^{-1}$ $\frac{4\pi}{\Delta m^2_{21}} \approx 33\ \mathrm{km} \cdot \mathrm{MeV}^{-1}$

$\sin^2(2\theta_{13}) \approx 0.08$ $\sin^2(2\theta_{12}) \approx 0.85$

Neutrino Oscillation

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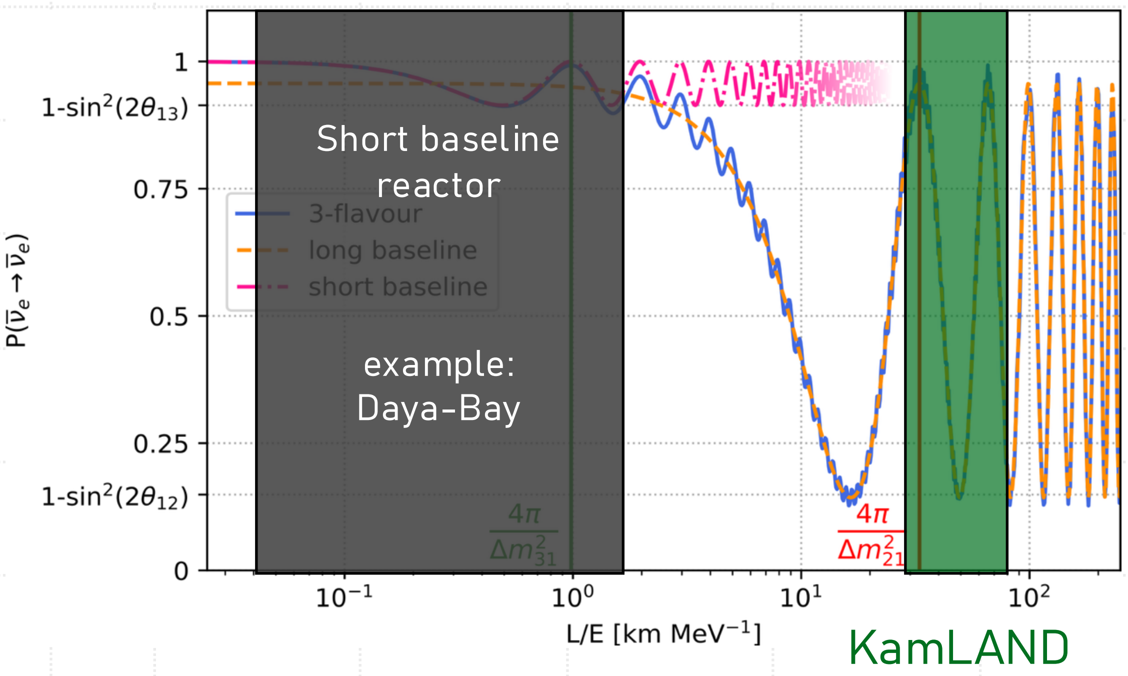

PDG 2025:

$$\Delta m^2_{21} = (7.50 \pm 0.19) \cdot 10^{-5}\ \text{eV}^2$$

$$s^2_{12} = 0.307 \pm 0.012$$

KamLAND [1] (reactor):

$$\Delta m^2_{21} = (7.54^{+0.19}_{-0.18}) \cdot 10^{-5}\ \text{eV}^2$$

SuperK & SNO [2] (solar):

$$s^2_{12} = 0.306 \pm 0.013$$

[1] Phys. Rev. D 88, 033001 (2013), 1303.4667
[2] Phys. Rev. D 109, 092001 (2024), 2312.12907

Neutrino Oscillation

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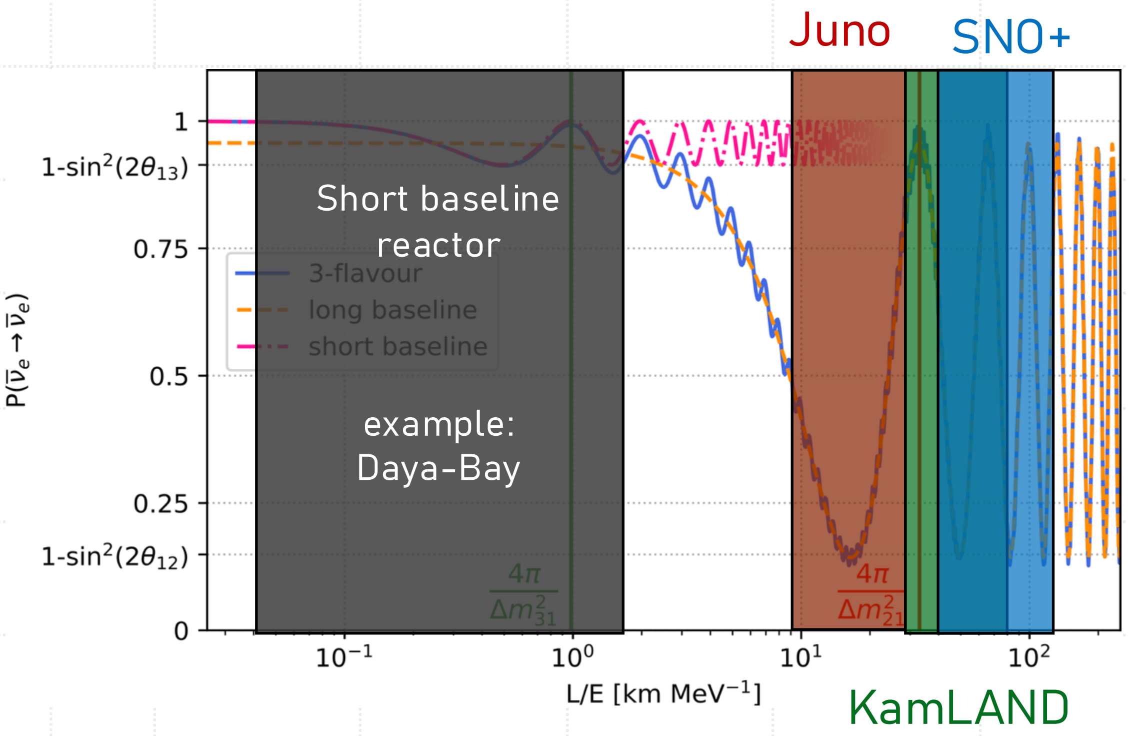

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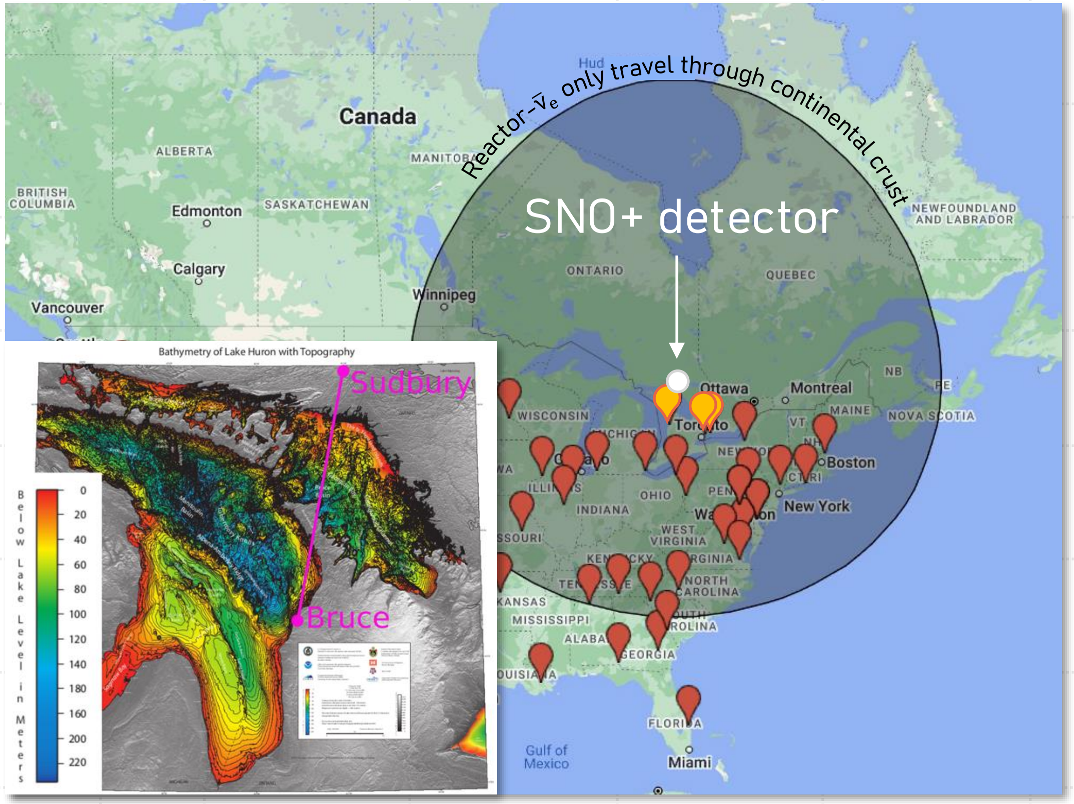
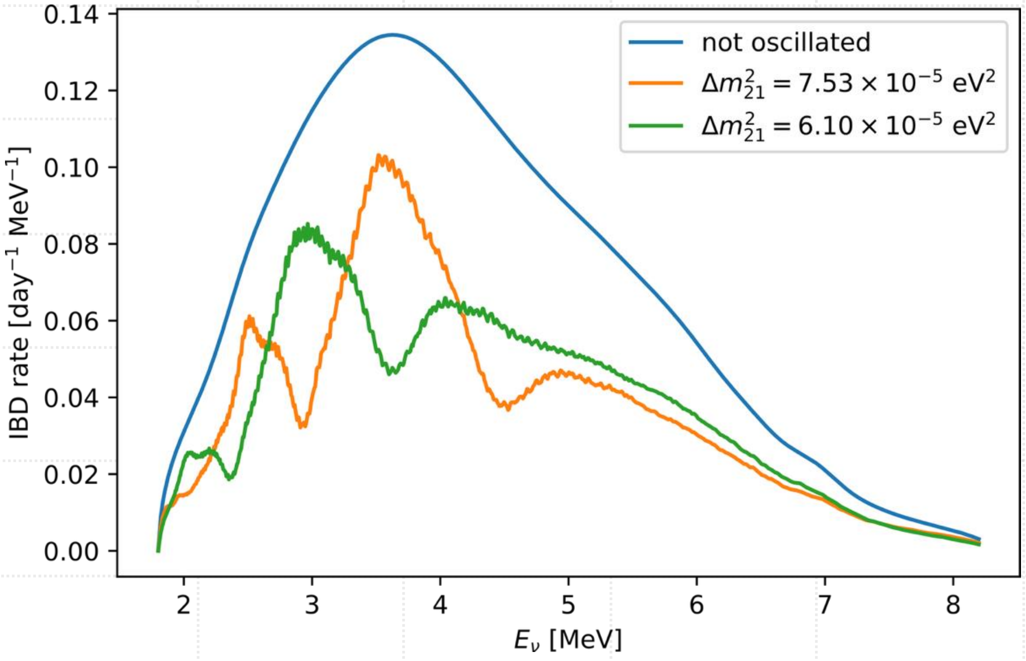
Reactor Antineutrinos



- SNO+ $\bar{\nu}_e$ flux dominated by the 3 Ontario reactor complexes:
  - Bruce, at 240 km → 40%
  - Pickering & Darlington, at ~345 km → 20%
- Example Antineutrino spectra, via inverse beta decays (IBD):

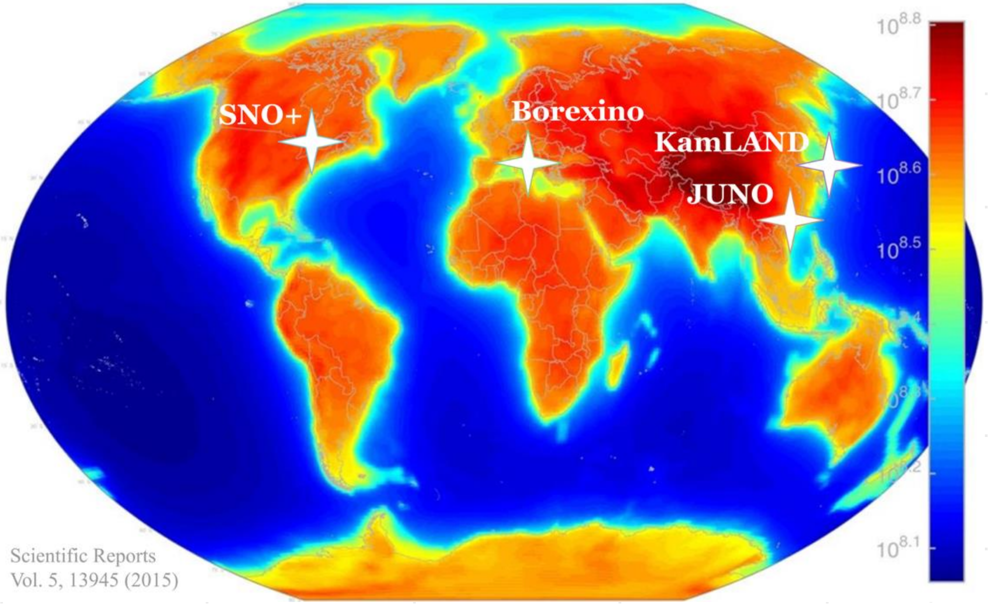


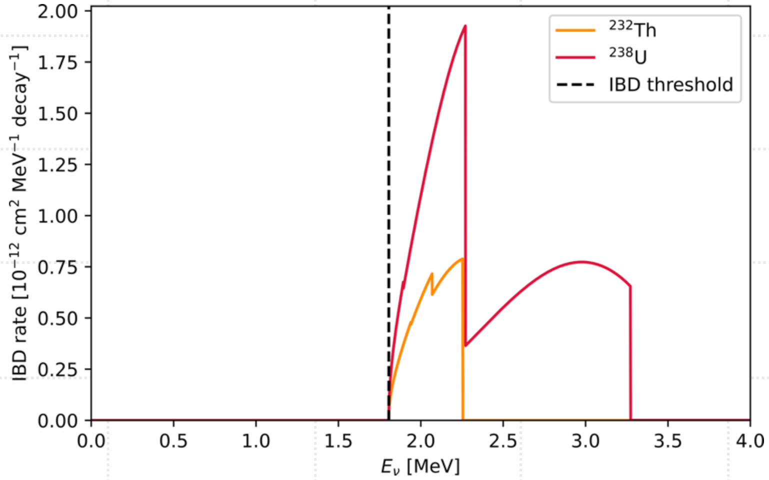
Geo-Neutrinos

- Radiogenic heat from inside the Earth due primarily to radioactive decays
- Emission of $\bar{\nu}_e$ allows measurement of inner Earth composition
- Detected via IBDs

- **Large uncertainty** in the flux
- Multiple measurement locations allows better constraints
  - For example, measuring the mantle's contribution
  - **Measured at 4 locations** so far, including SNO+

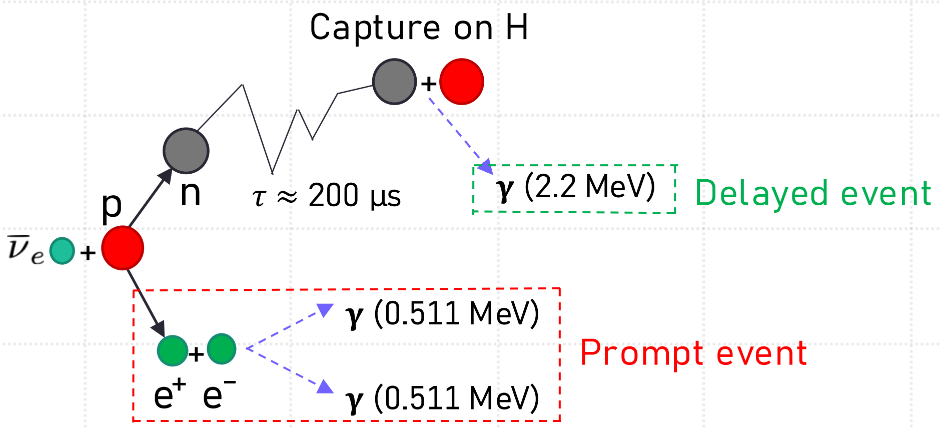
$\bar{\nu}_e$ flux map & geo-ν measurement locations





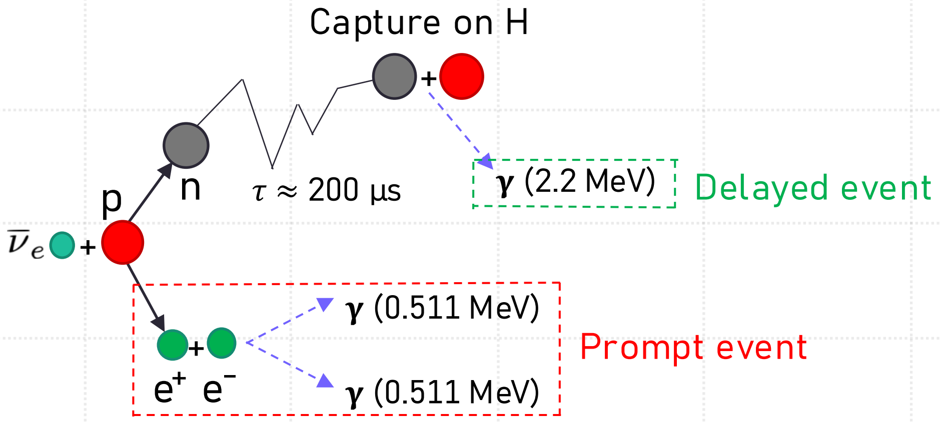
The Signal: IBDs

- Prompt energy highly correlated to $\bar{\nu}_e$ energy ($E \approx E_\nu - 0.8$ MeV)



The Signal: IBDs

- Prompt energy highly correlated to $\bar{\nu}_e$ energy ($E \approx E_\nu - 0.8$ MeV)
- Coincidence tagging eliminates most backgrounds:



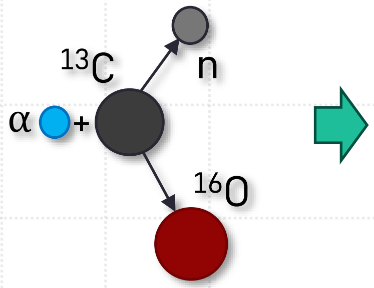
Cuts	Prompt	Delayed
Energy [MeV]	0.9 - 8.0	1.85 - 2.5
$|\Delta\vec{r}|$ [m]	< 2.5	
Δt [μs]	< 2000	
Radial position [m]	< 5.7	

- Accidental coincidences further reduced by likelihood classifier (Δt, $|\Delta\vec{r}|$, delayed E)
- Reduced to negligible level.

Background: (α, n) Events

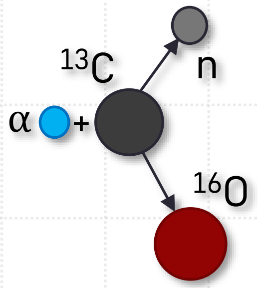
Triggered by α particles from ^{210}Po decays capturing on ^{13}C inside the detector:

Prompt + neutron capture mimics IBD!



$^{13}C(\alpha\text{-}n)^{16}O$ prompt events
Proton recoil
^{12}C scattering
^{16}O deexcitation

Background: (α, n) Events



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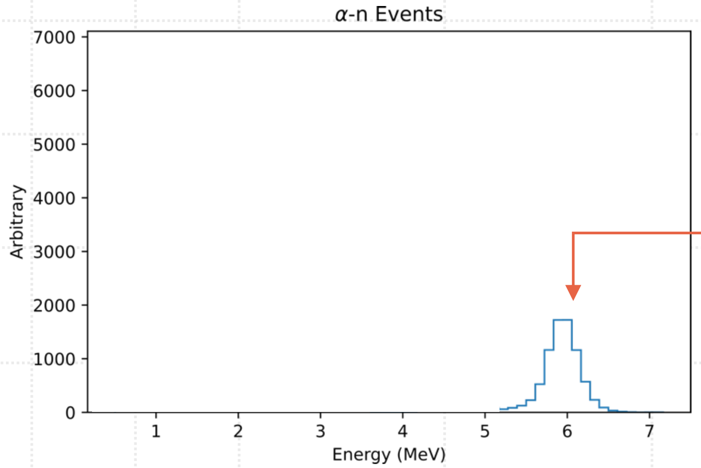
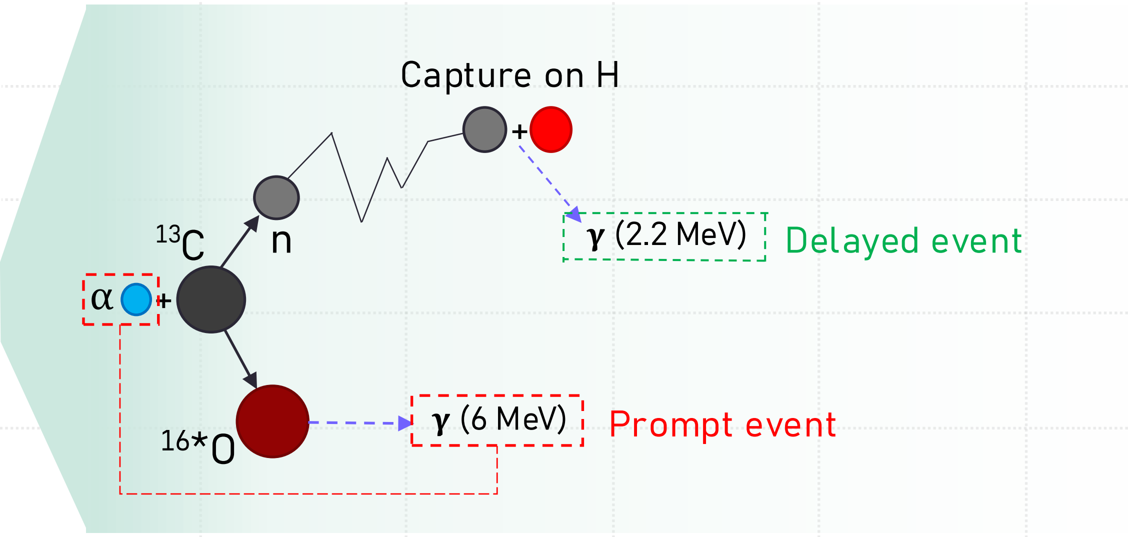
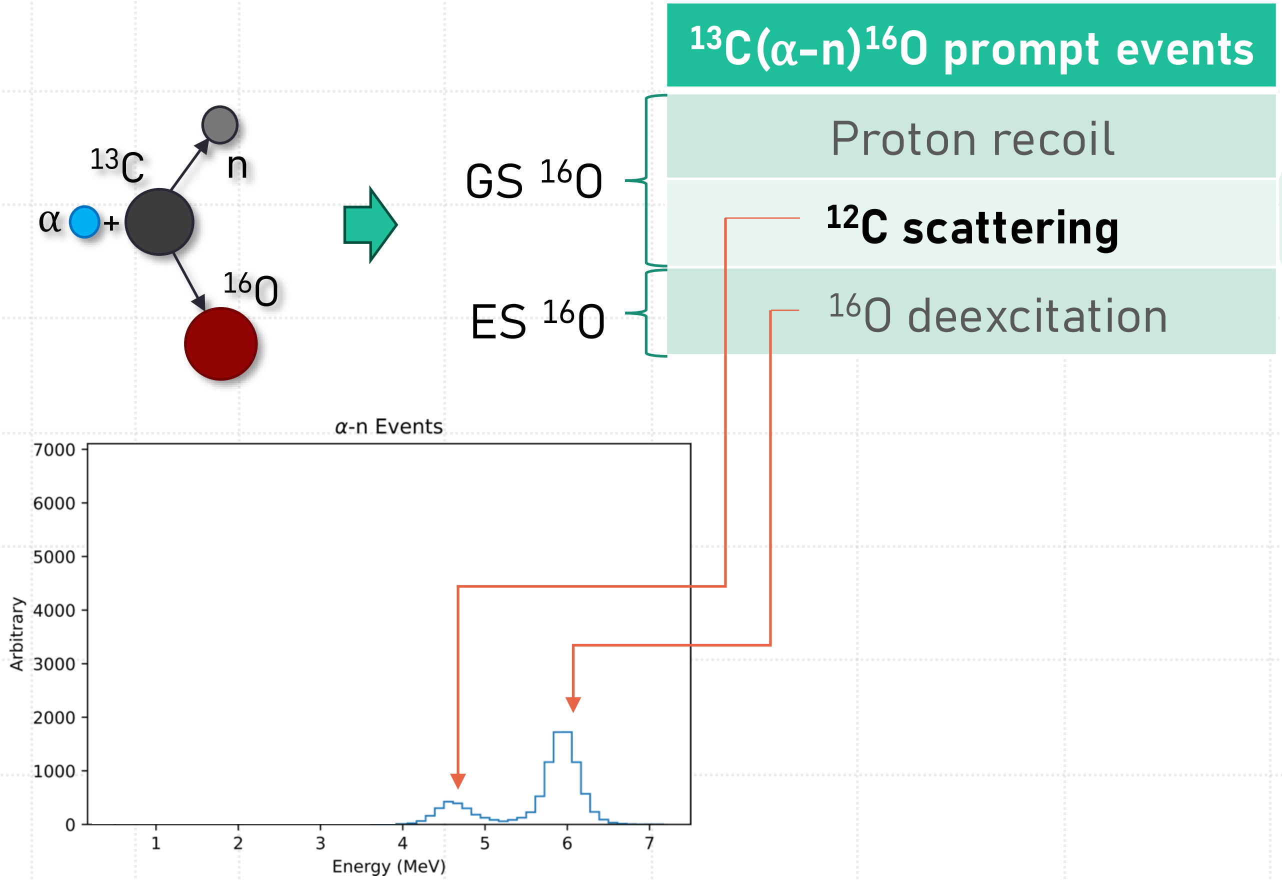
ES ^{16}O

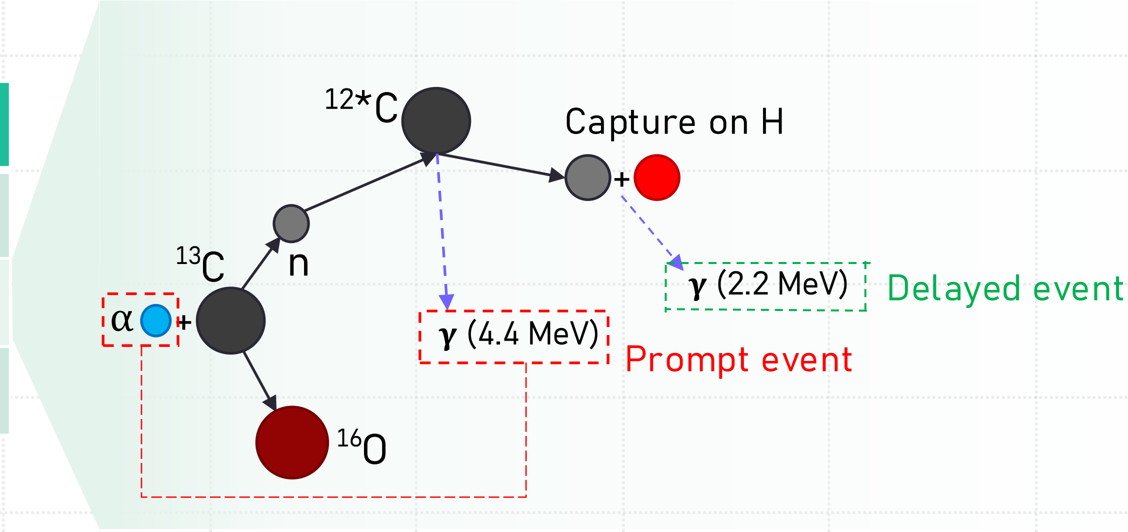




- Oxygen produced in excited state(s).
- Releases **γ** or e^-e^+ pair **~6 MeV**.

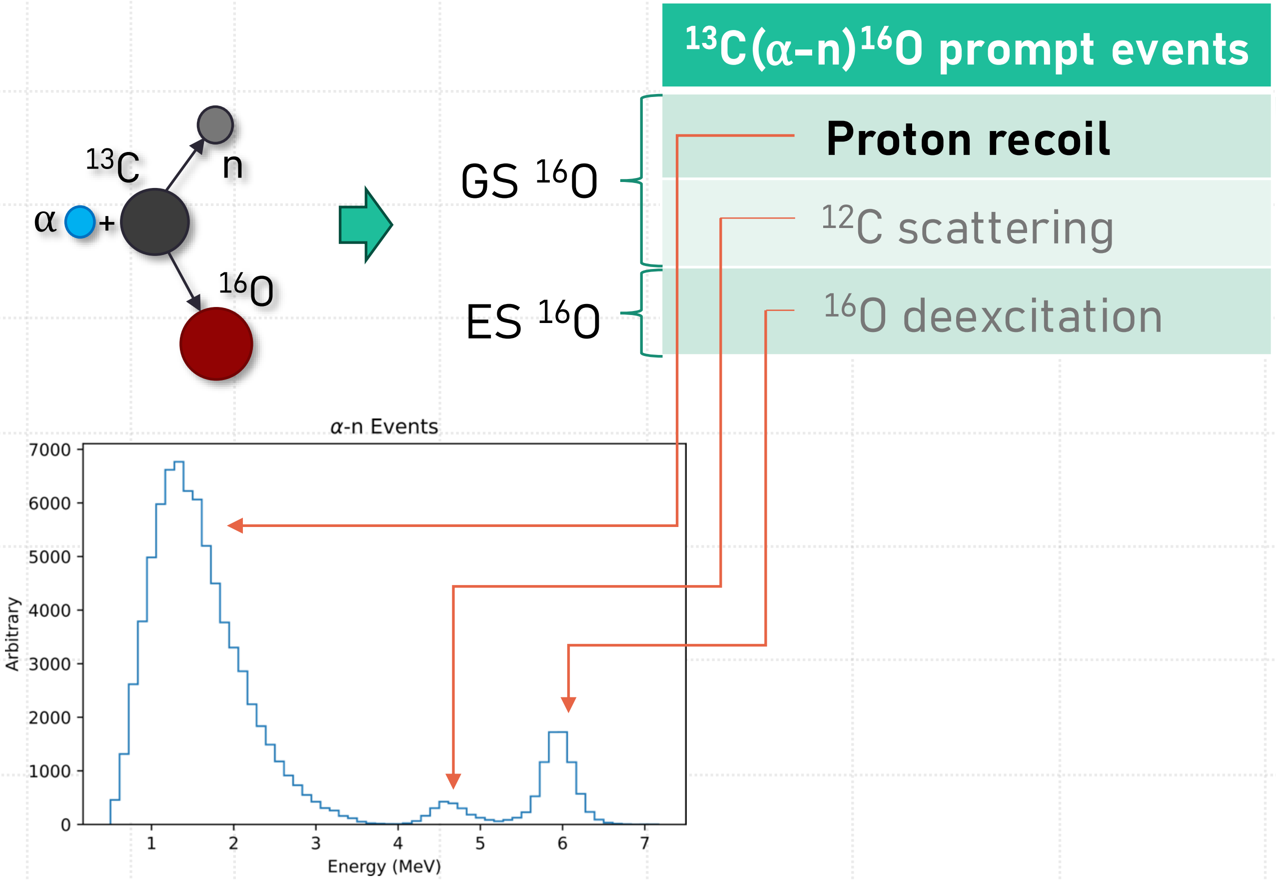
Background: (α, n) Events

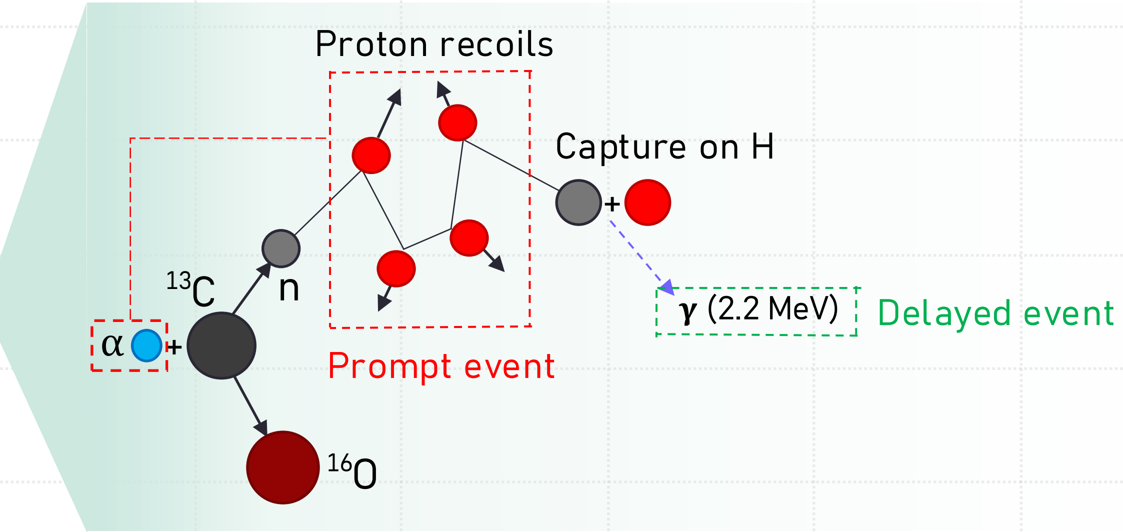




- Oxygen produced in ground state.
- Neutron takes away most of the energy.
- Inelastically scatters off ^{12}C in medium.
- Releases **4.4 MeV γ**.

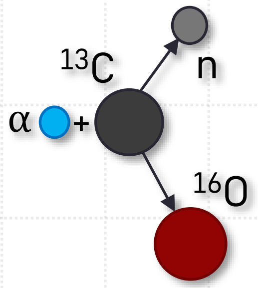
Background: (α, n) Events





- Elastically scatter off protons (for a few ns).
- Reconstructed events in **0.4–3.8 MeV range**.

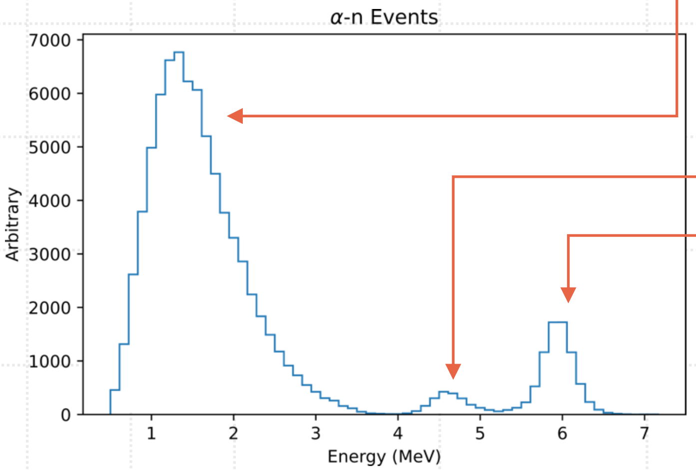
Background: (α, n) Events

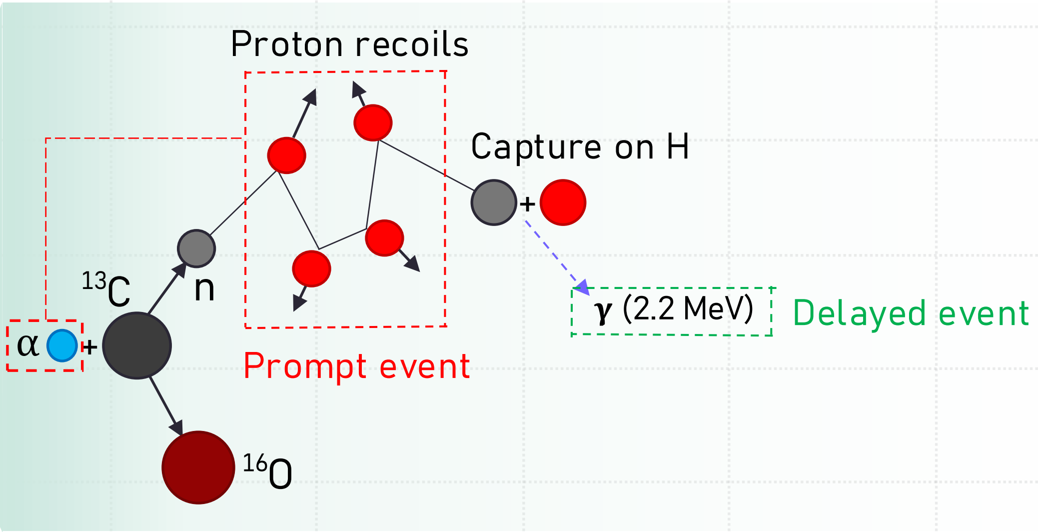


$^{13}C(\alpha\text{-}n)^{16}O$ prompt events

GS ^{16}O
- **Proton recoil**
- ^{12}C scattering

ES ^{16}O
- ^{16}O deexcitation



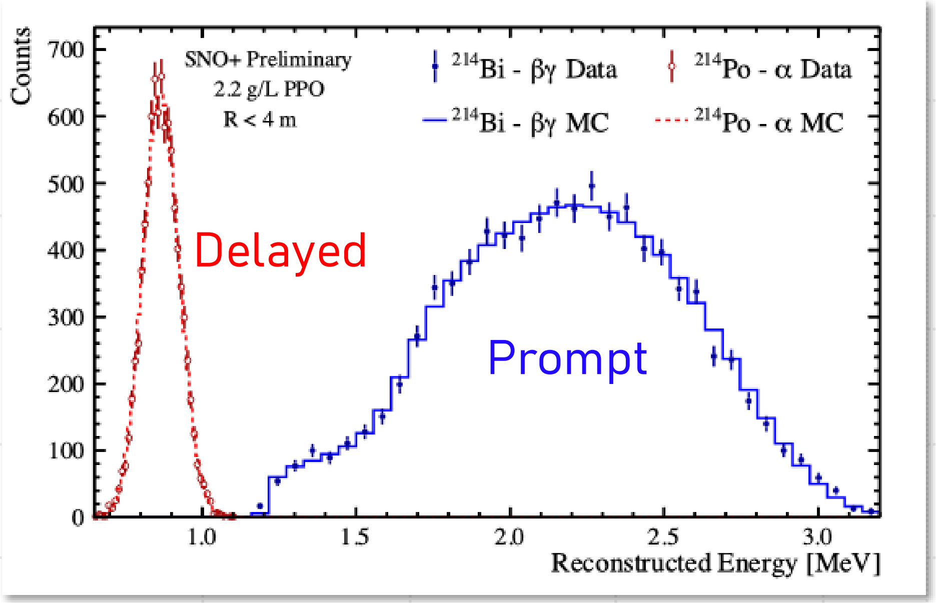


- Proton quenching is measured using a deployed ^{241}Am–^{9}Be neutron source.

See talk by Anthony Allega on AmBe calibration at SNO+!

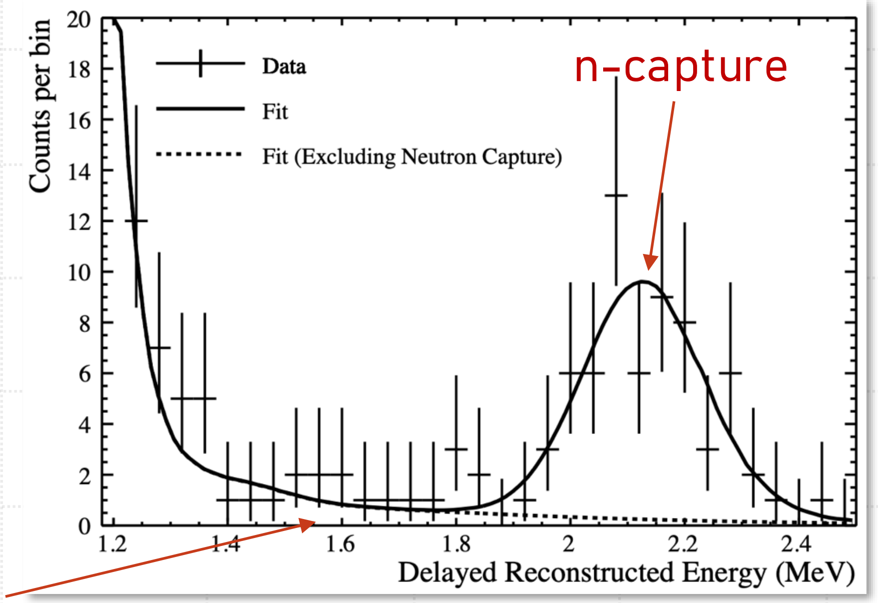
Background: α-p Events

^{214}BiPo



Internal ^{214}BiPo background:

- ^{214}Bi → β-decay to ^{214}Po → α-decay to ^{210}Pb
- Δt = 237μs (^{214}Po lifetime)
- α can scatter off protons, which have less quenching → high energy tail enters delayed energy window
- Identified as a background by SNO+ *



*Phys. Rev. Lett. **135**, 121801

IBD Candidates

Predictions in 685 days of live-time
(systematic uncertainties)

Reactor IBD	140 ± 6
Geo ^{238}U IBD	29
Geo ^{232}Th IBD	8
(α, n) p-scatters	80 ± 24
(α, n) other	12 ± 10
α-p	7 ± 6
Atmospheric ν	4 ± 3
Sum	281

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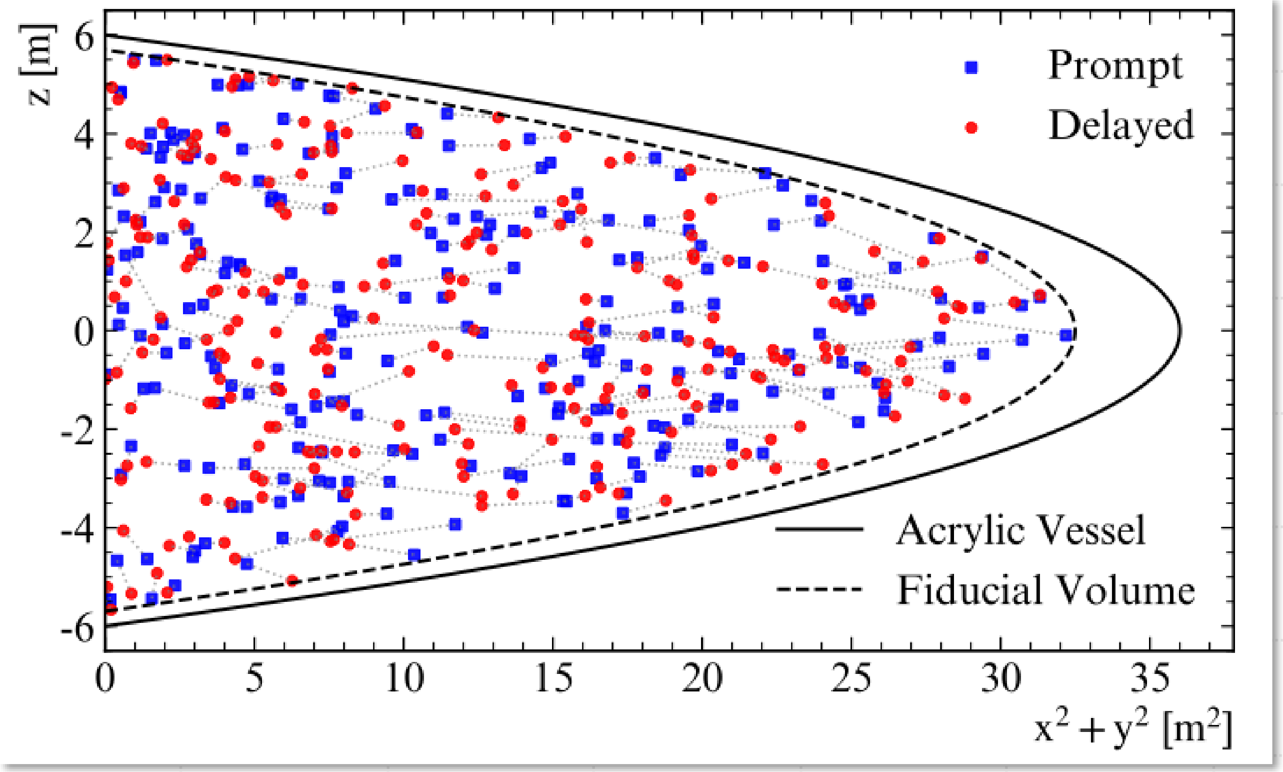
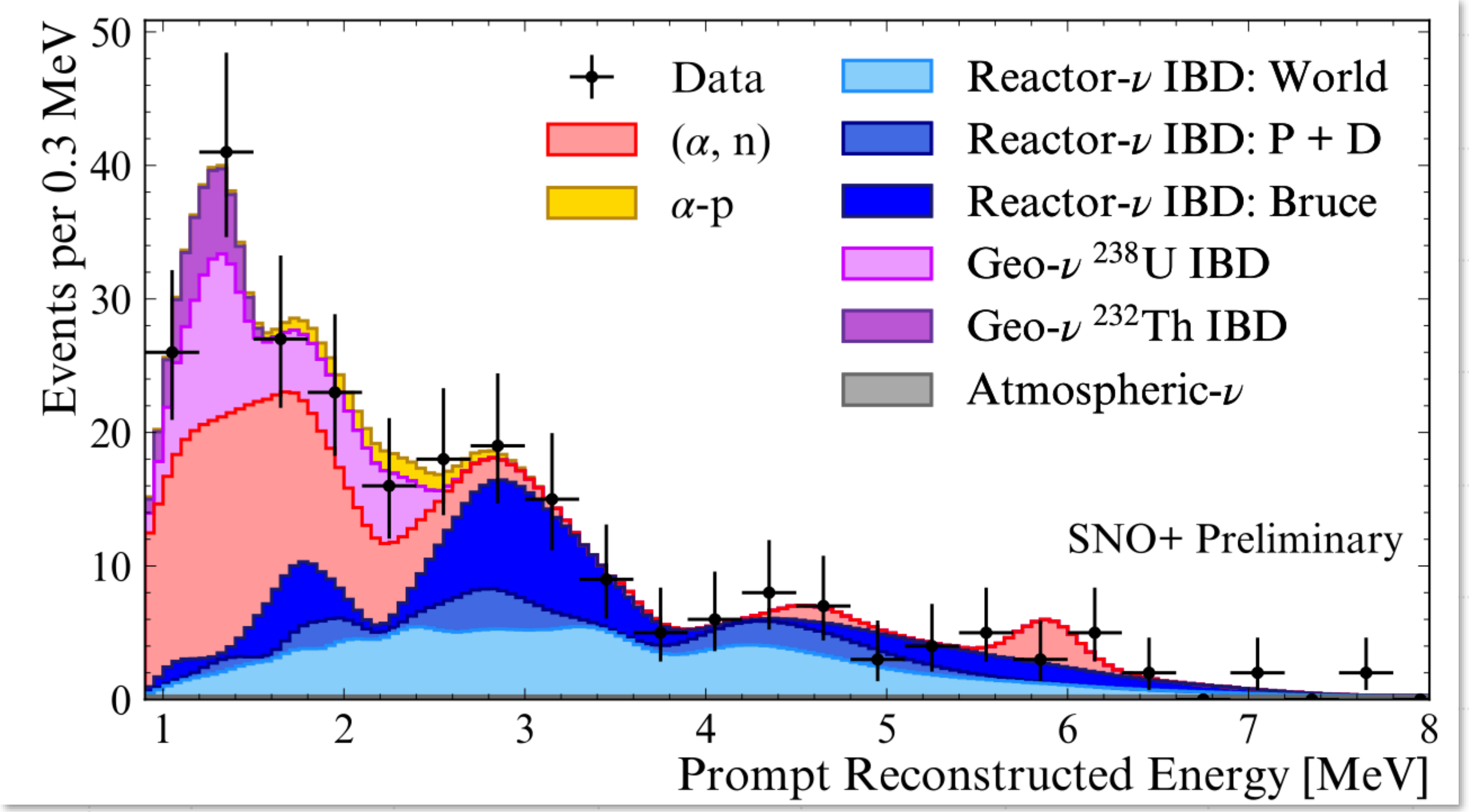
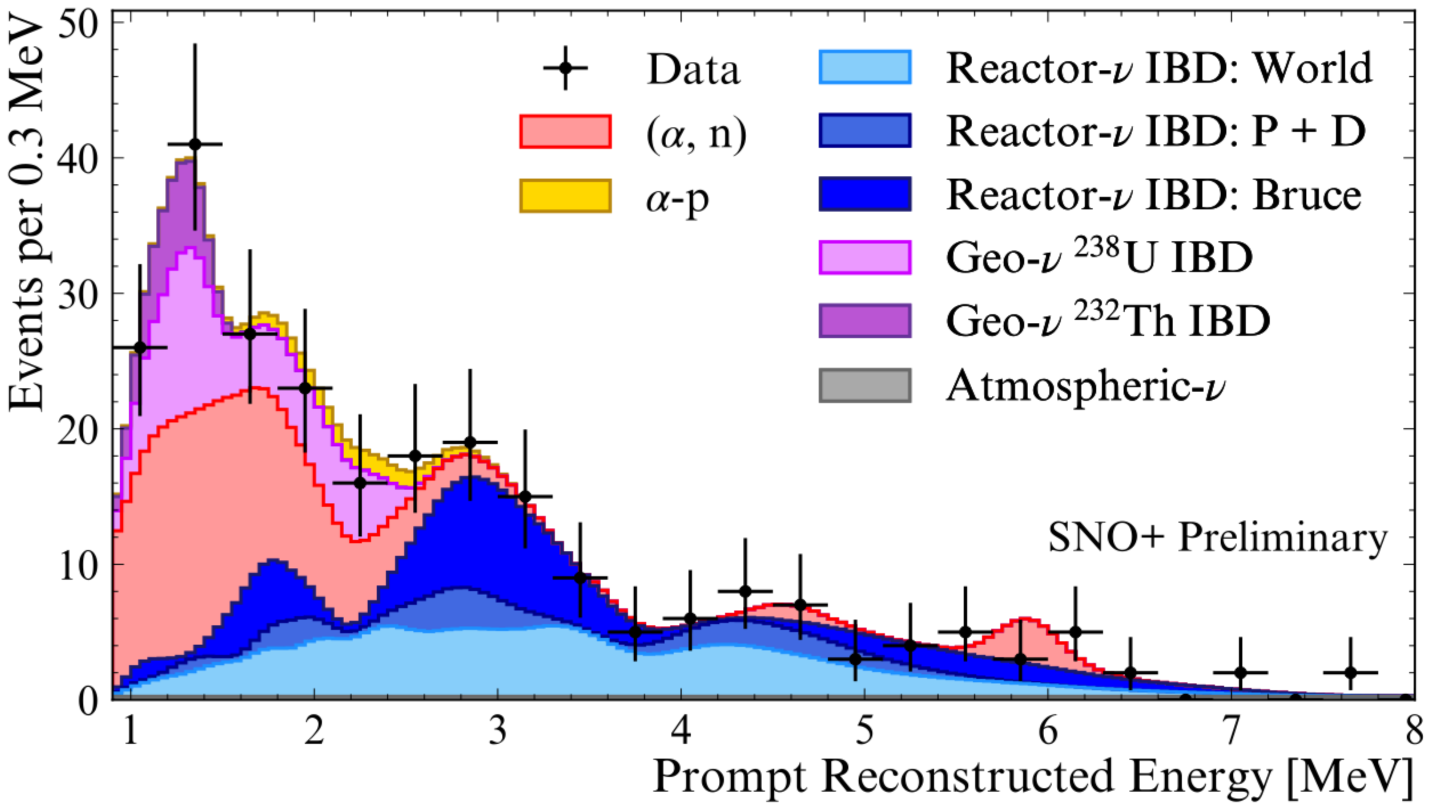
246 events tagged



Prompt Energy Spectrum



Oscillation Results



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$\sin^2\theta_{12}$	0.505 ± 0.134
Geo-$\overline{\nu}$ [TNU]	60^{+23}_{-22}

TNU = Terrestrial Neutrino Units:
Number of IBD events per 10^{32} protons per year, for a 100% efficient detector.

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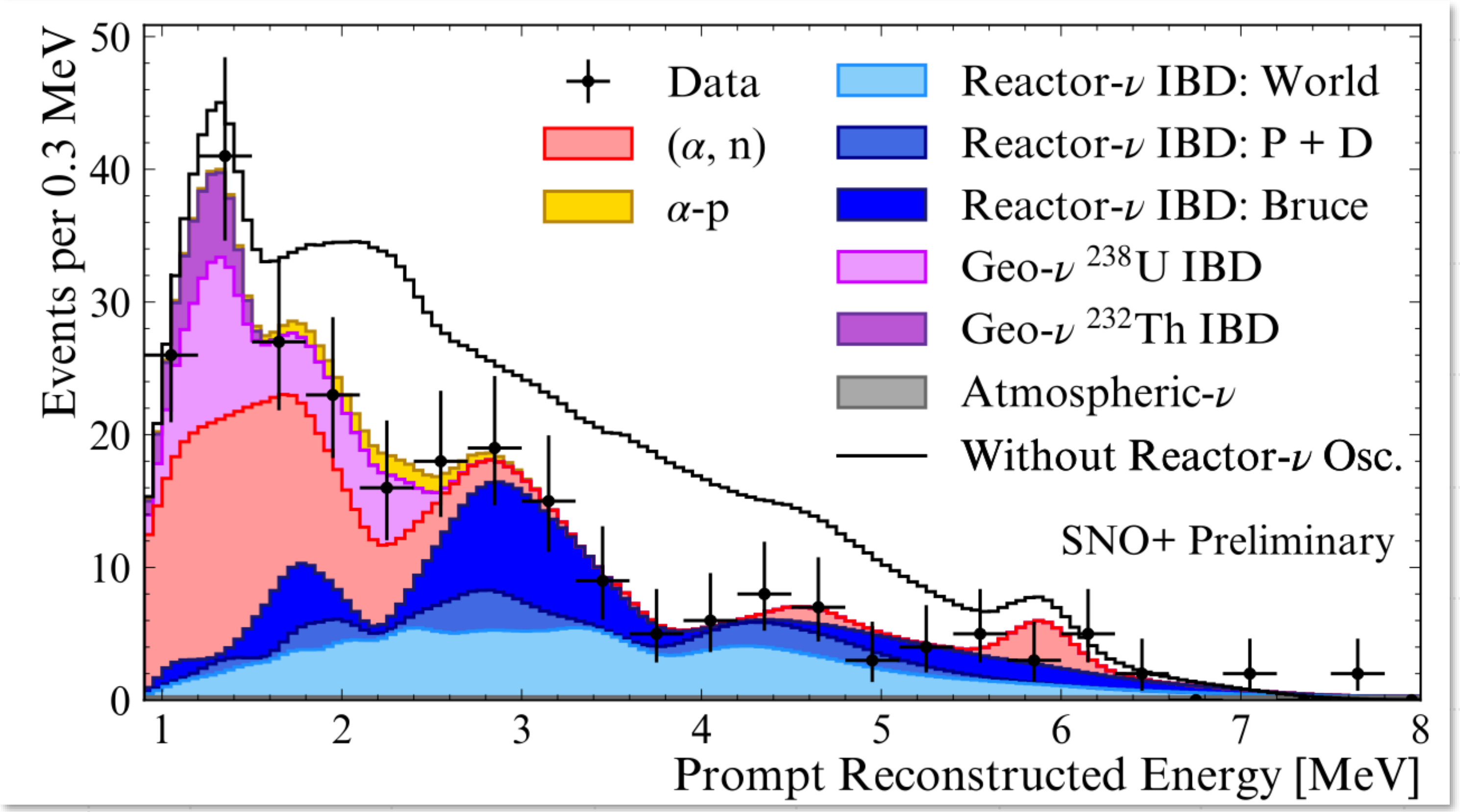

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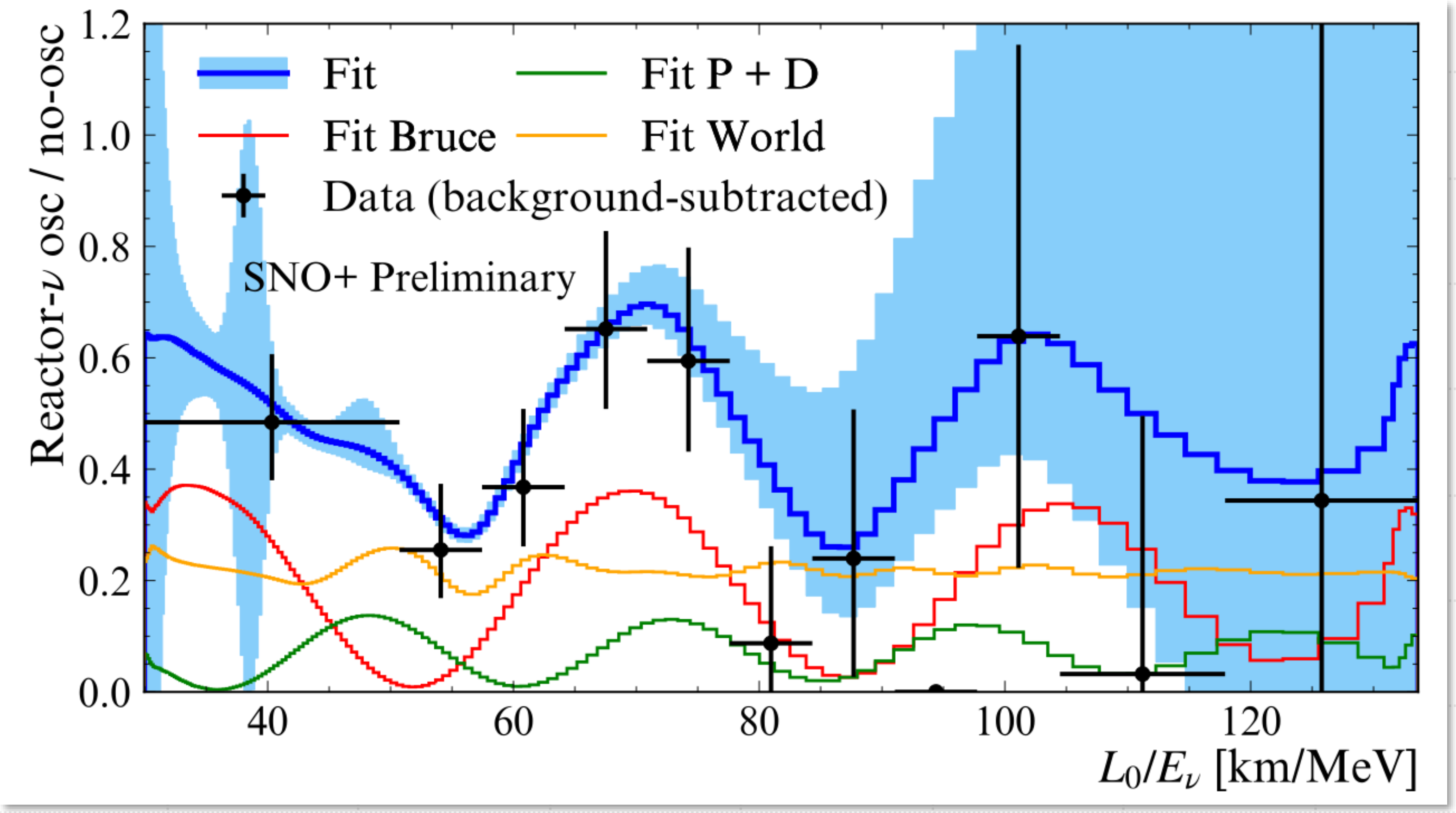
Oscillation Pattern

Ratio of reactor IBD spectrum with / without neutrino oscillation:



L_0 = 269 km

Oscillation Results

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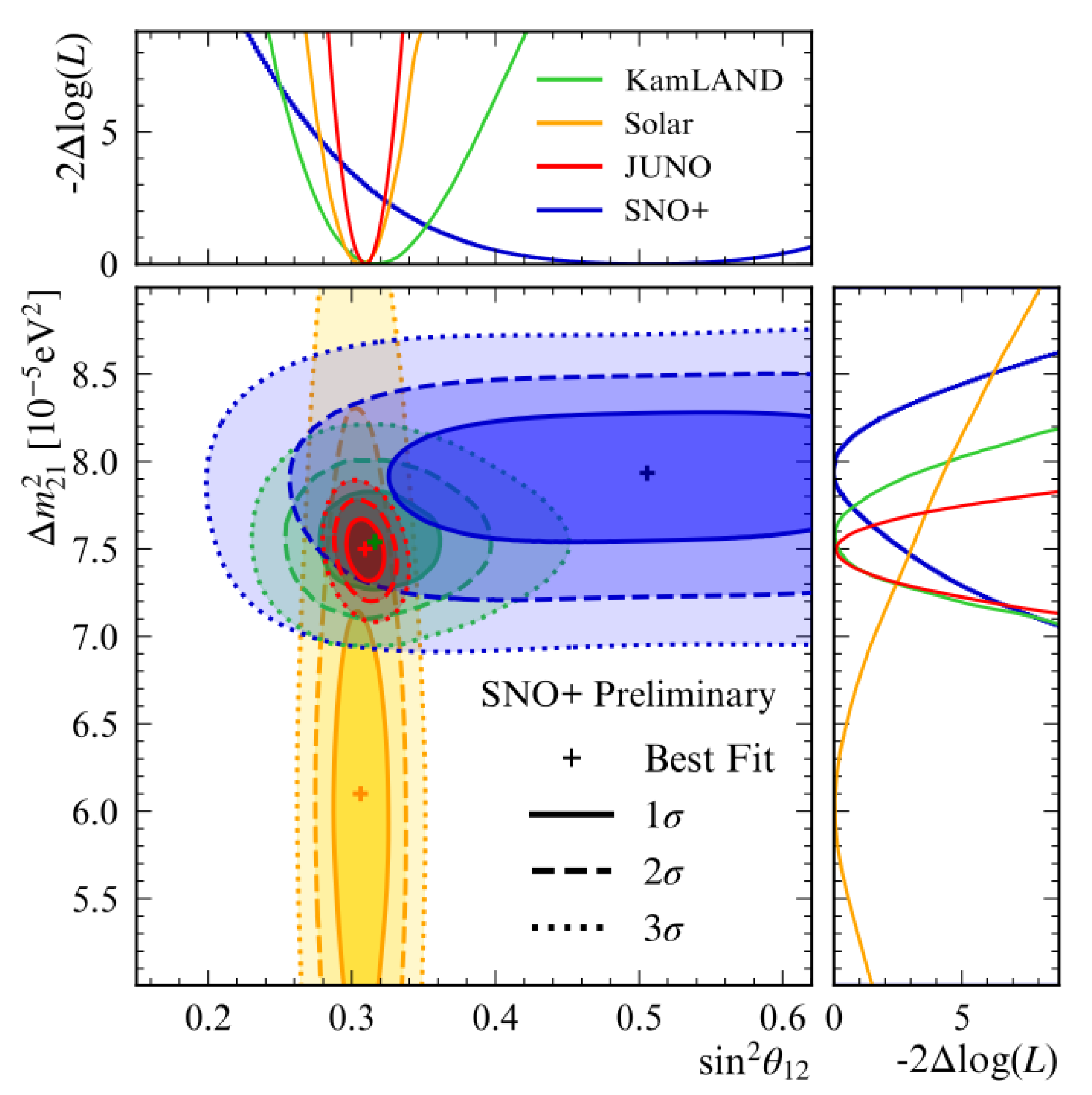

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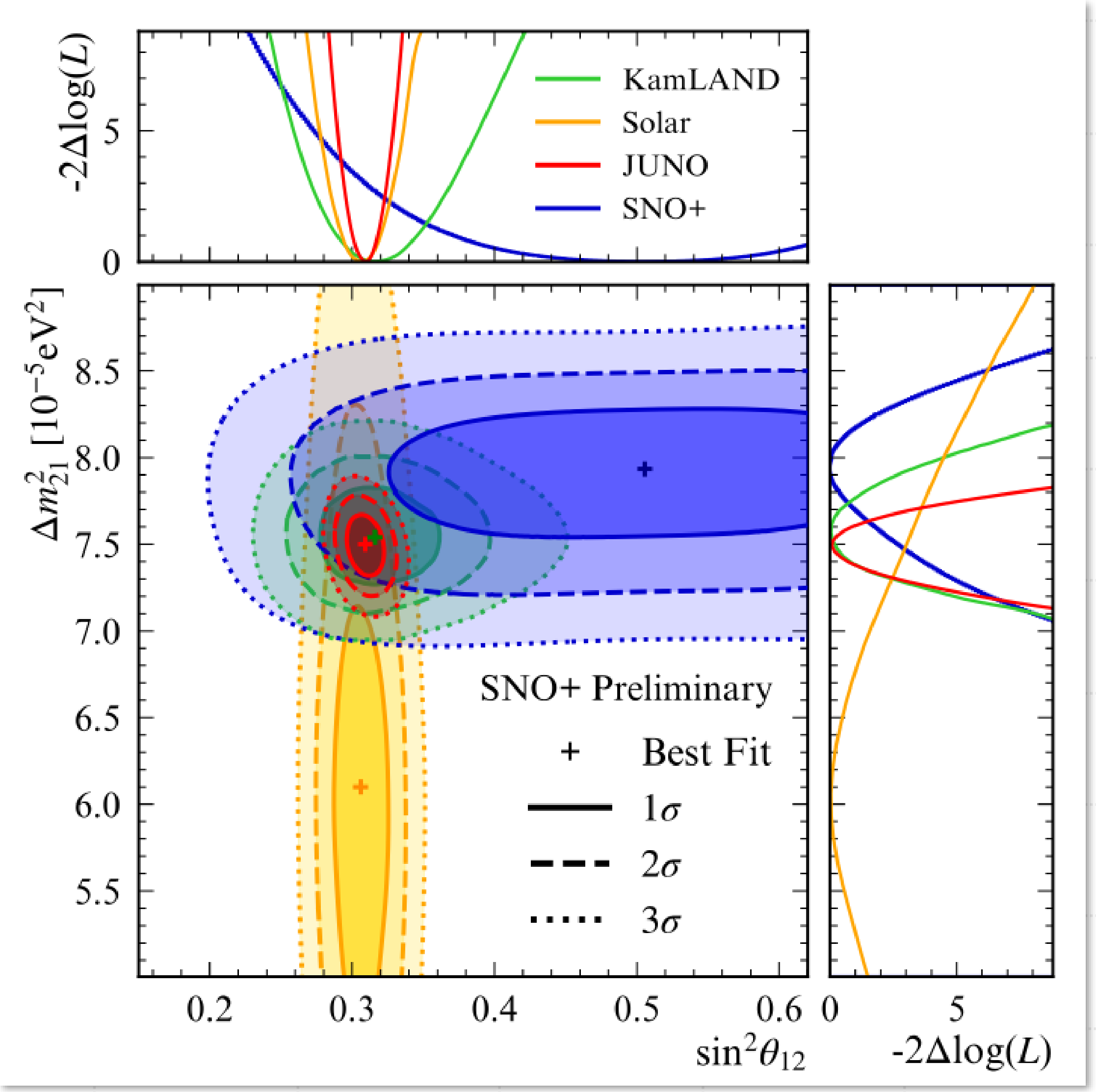
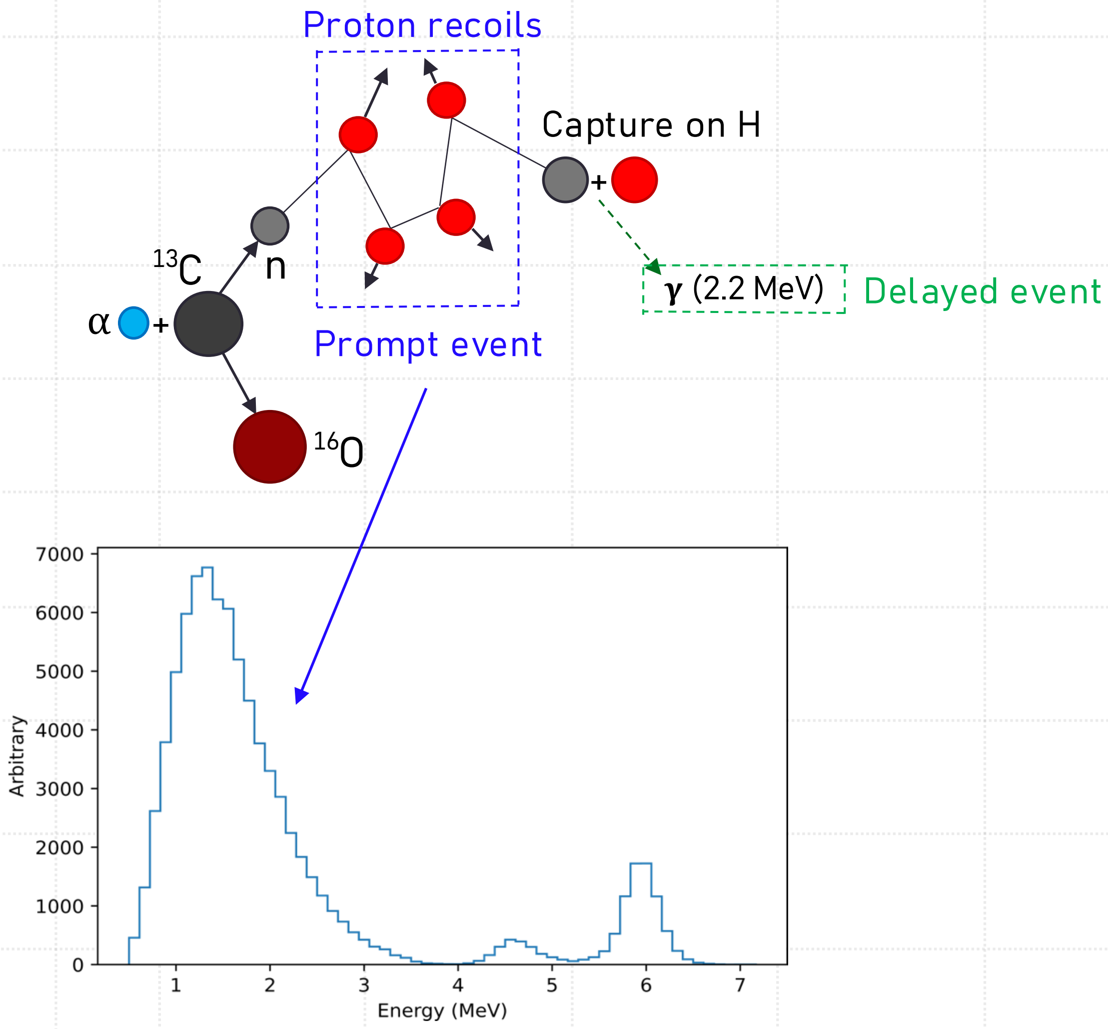
Can improve this measurement



Recall: (α, n) Proton Recoils



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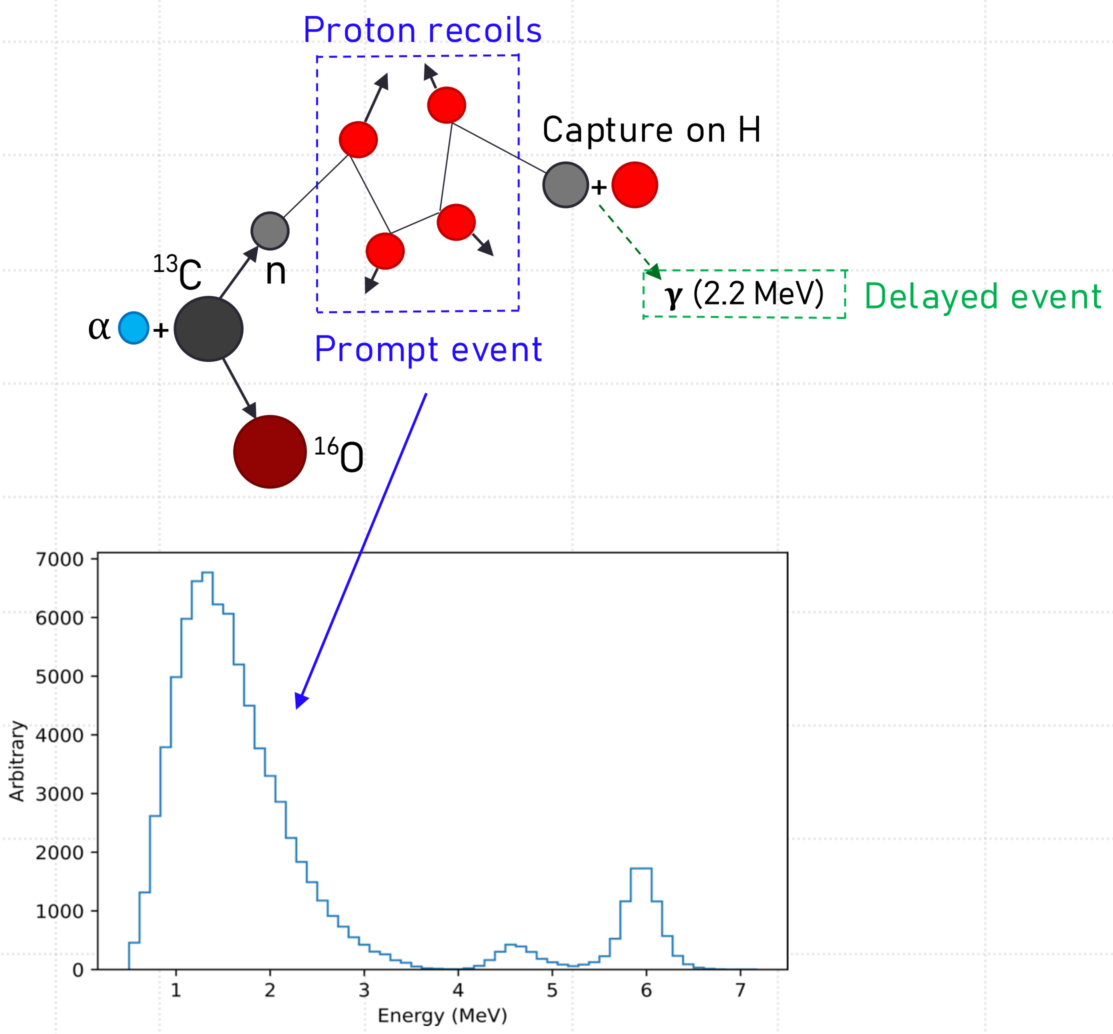
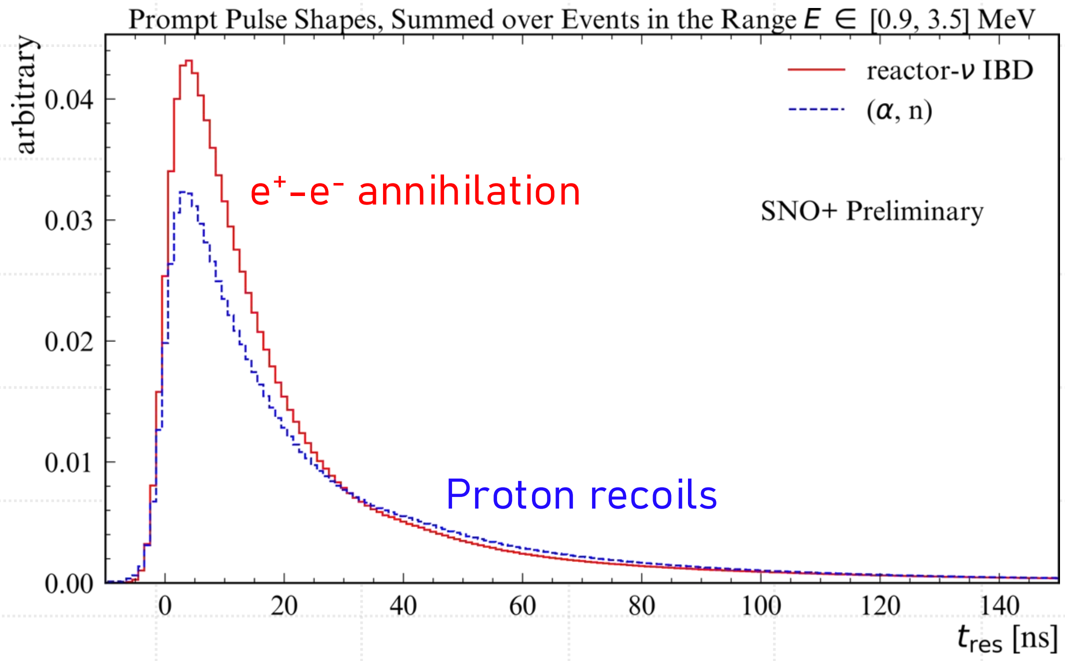
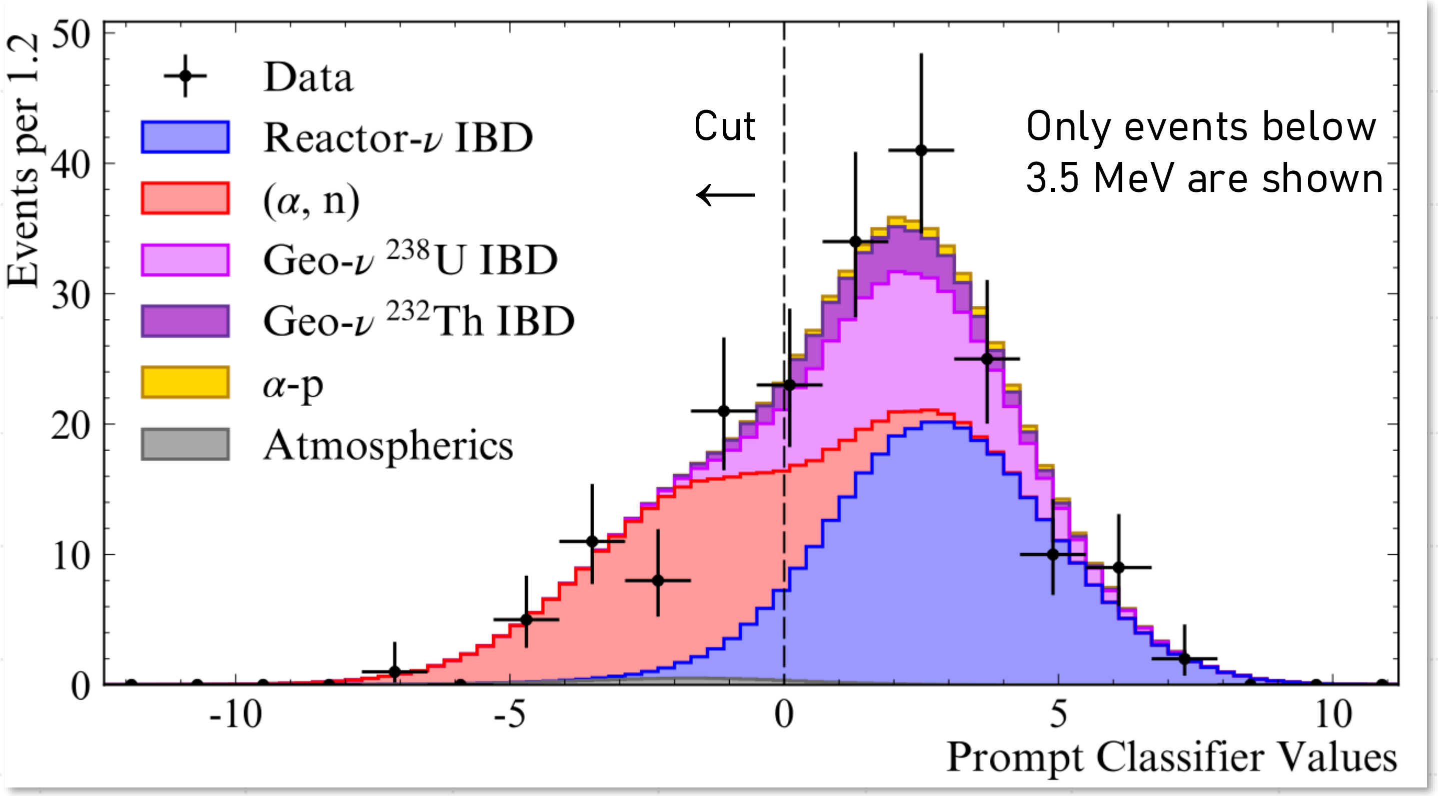


Multiple recoils → longer pulse shape:



(α, n)-IBD Classifier

Event-by-event classifier based on the Fisher discriminant

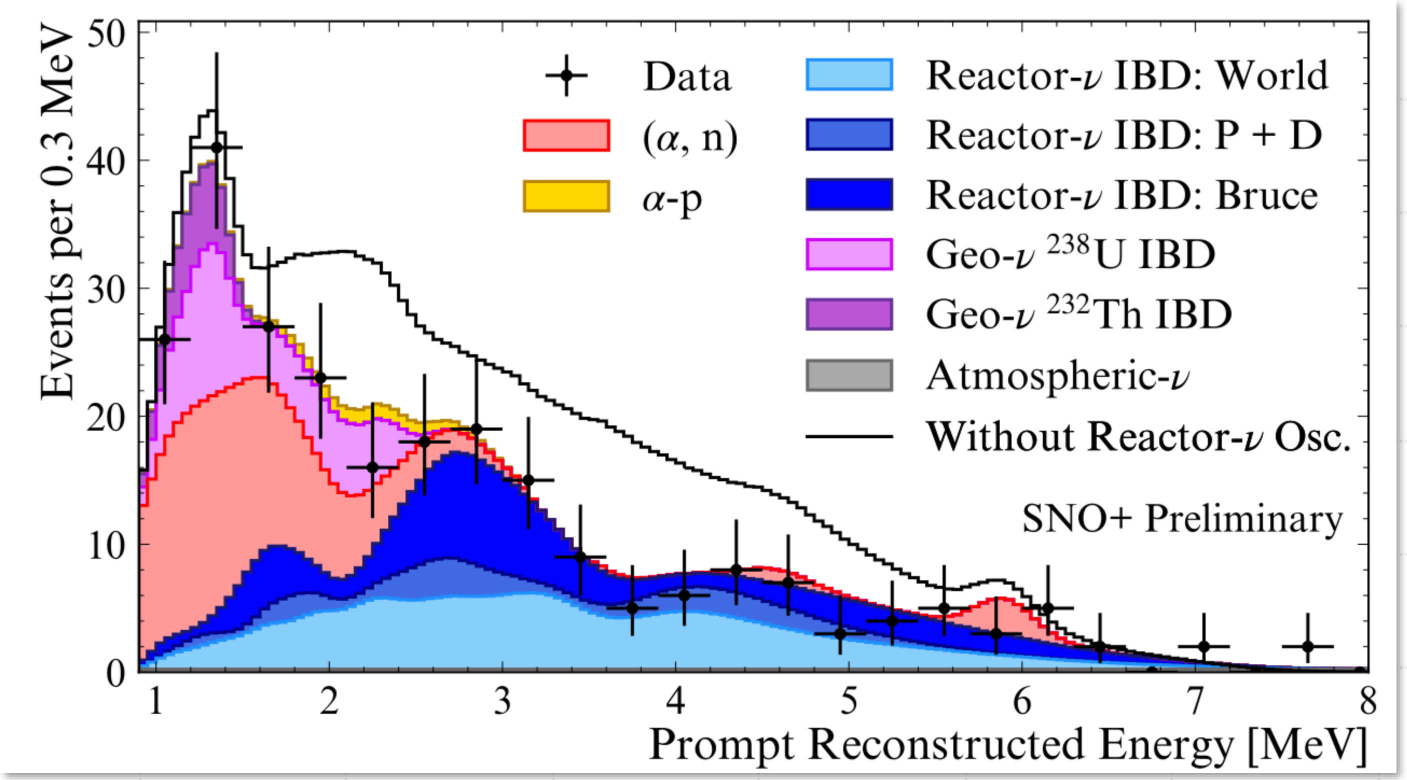


Selection efficiency below 3.5 MeV:

- (α, n) 11%
- IBD 90%

Classifier Cut

(α, n)-IBD cut below 3.5 MeV



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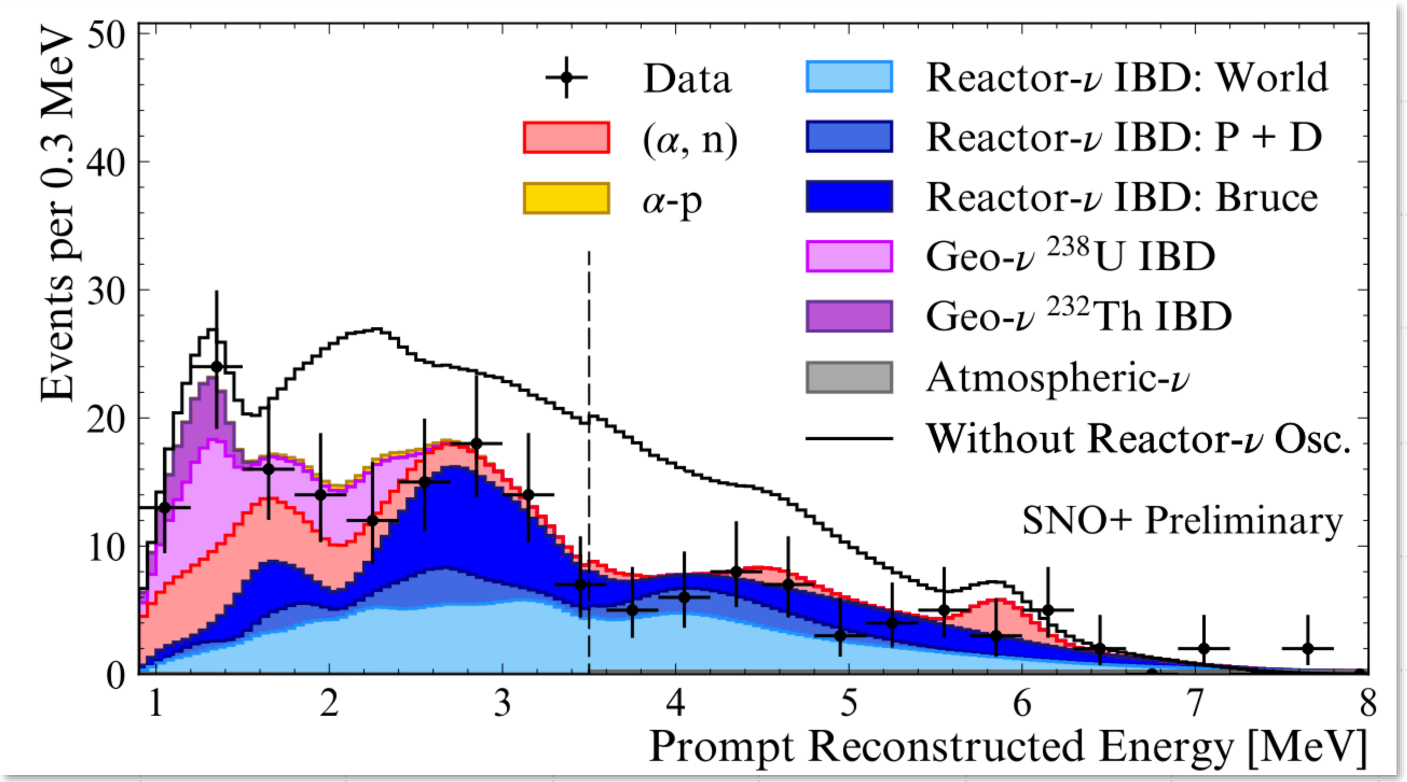
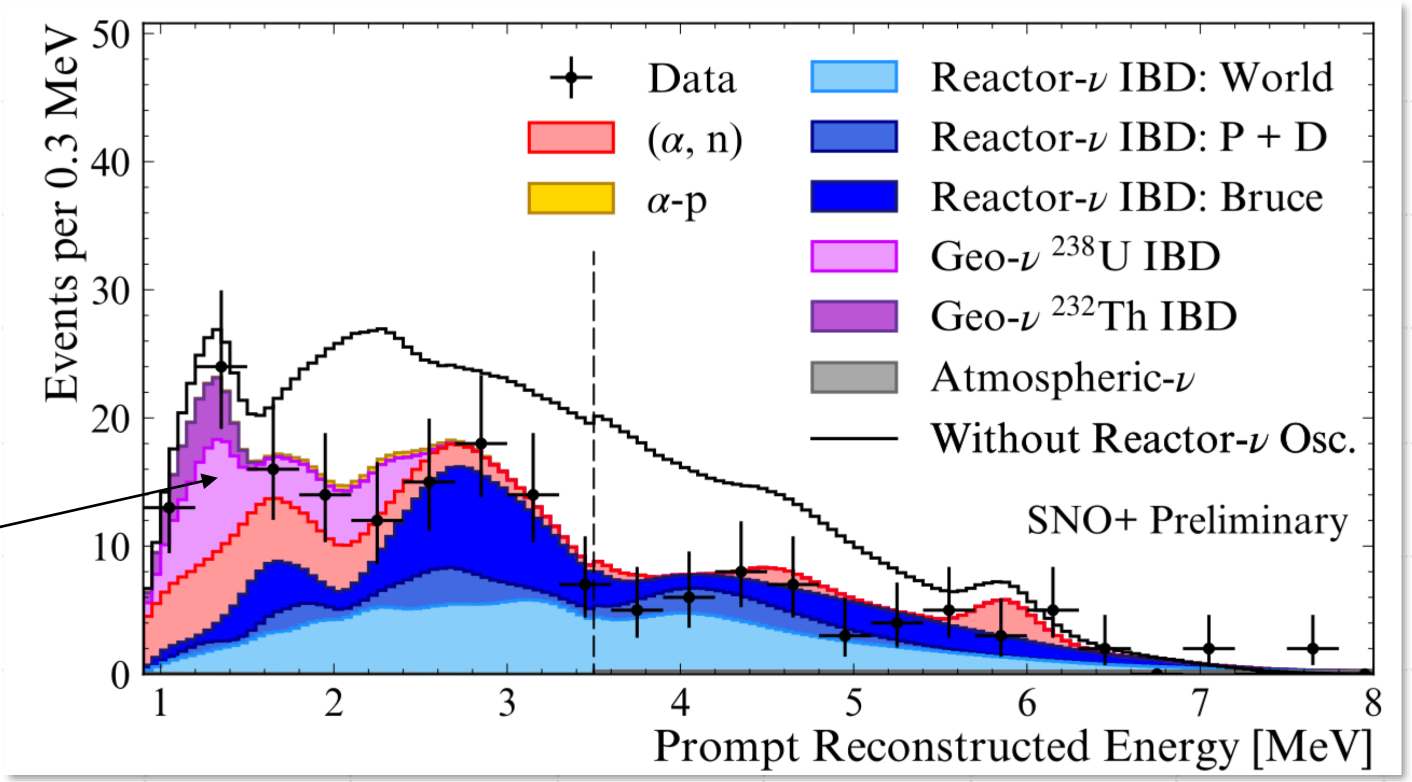


Classifier Cut

(α, n)-IBD cut below 3.5 MeV

49^{+13}_{-12} TNU



Geo-ν Rate

Increasing geo-ν flux expected

SNO+: 49^{+13}_{-12} TNU

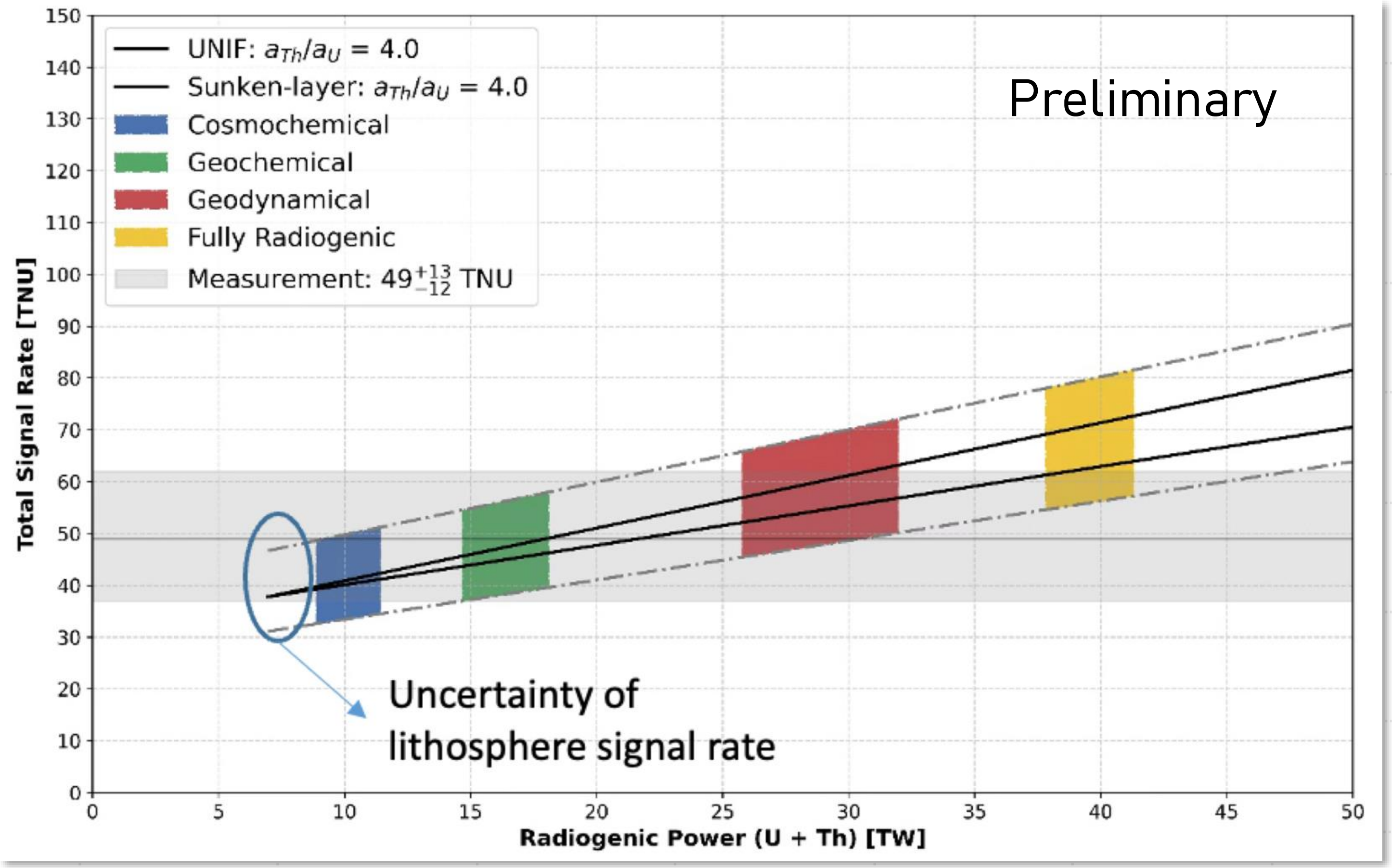
Borexino: $47^{+8.4}_{-7.7}(\text{stat})^{+2.4}_{-1.9}(\text{syst})$ TNU

KamLAND: $28.6^{+5.1}_{-4.8}$ TNU

Borexino – PHYS. REV. D 101, 012009 (2020)
KamLAND – Neutrino Geoscience 2025 Kingston: Geoneutrino Observation with KamLAND (https://indico.global/event/14476/contributions/136079/)

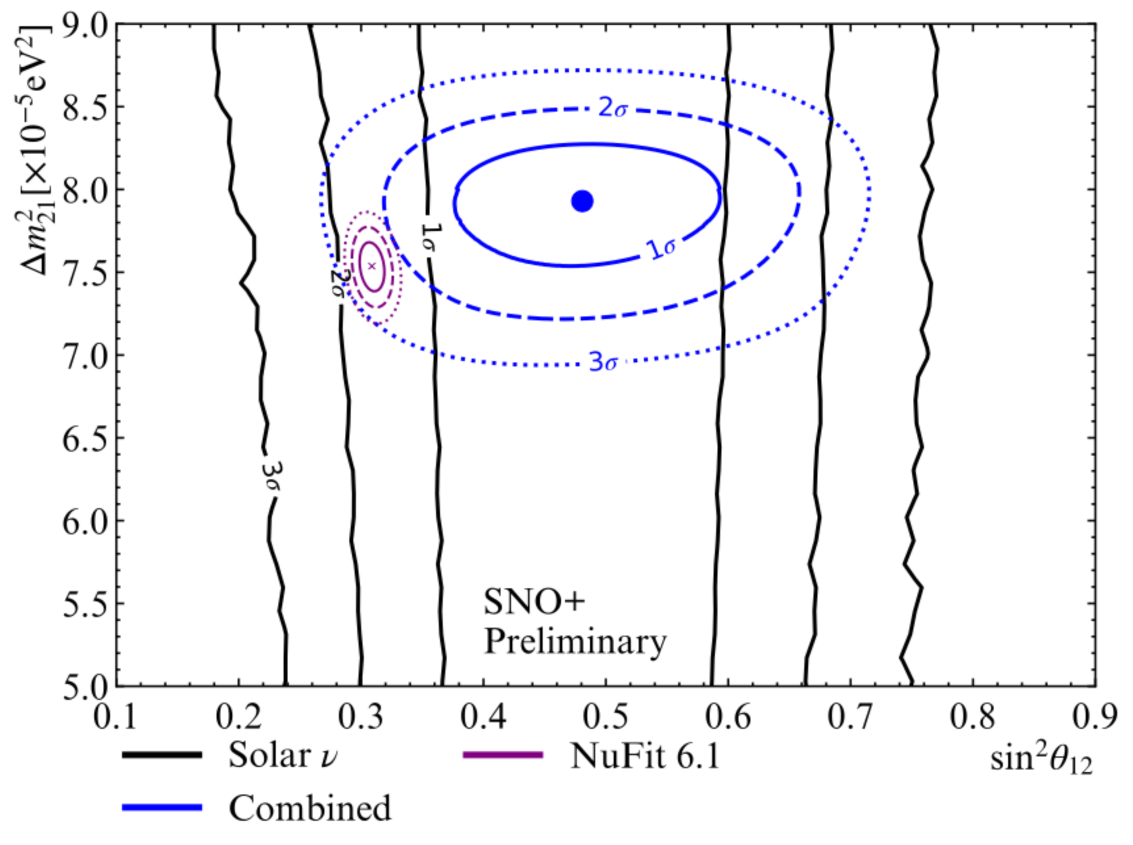
Geo-ν Interpretation

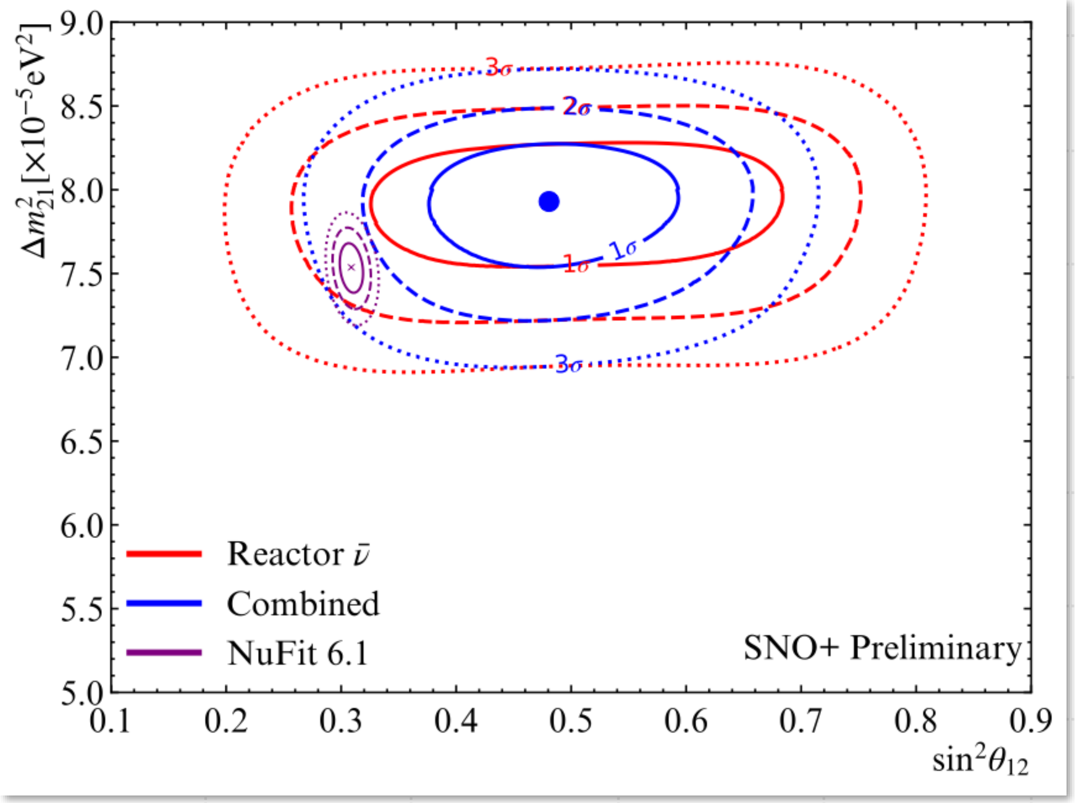
Geo-ν rate vs Radiogenic Heat at SNO+



Upcoming: Solar + Reactor

First solar + reactor oscillation fit in a single detector



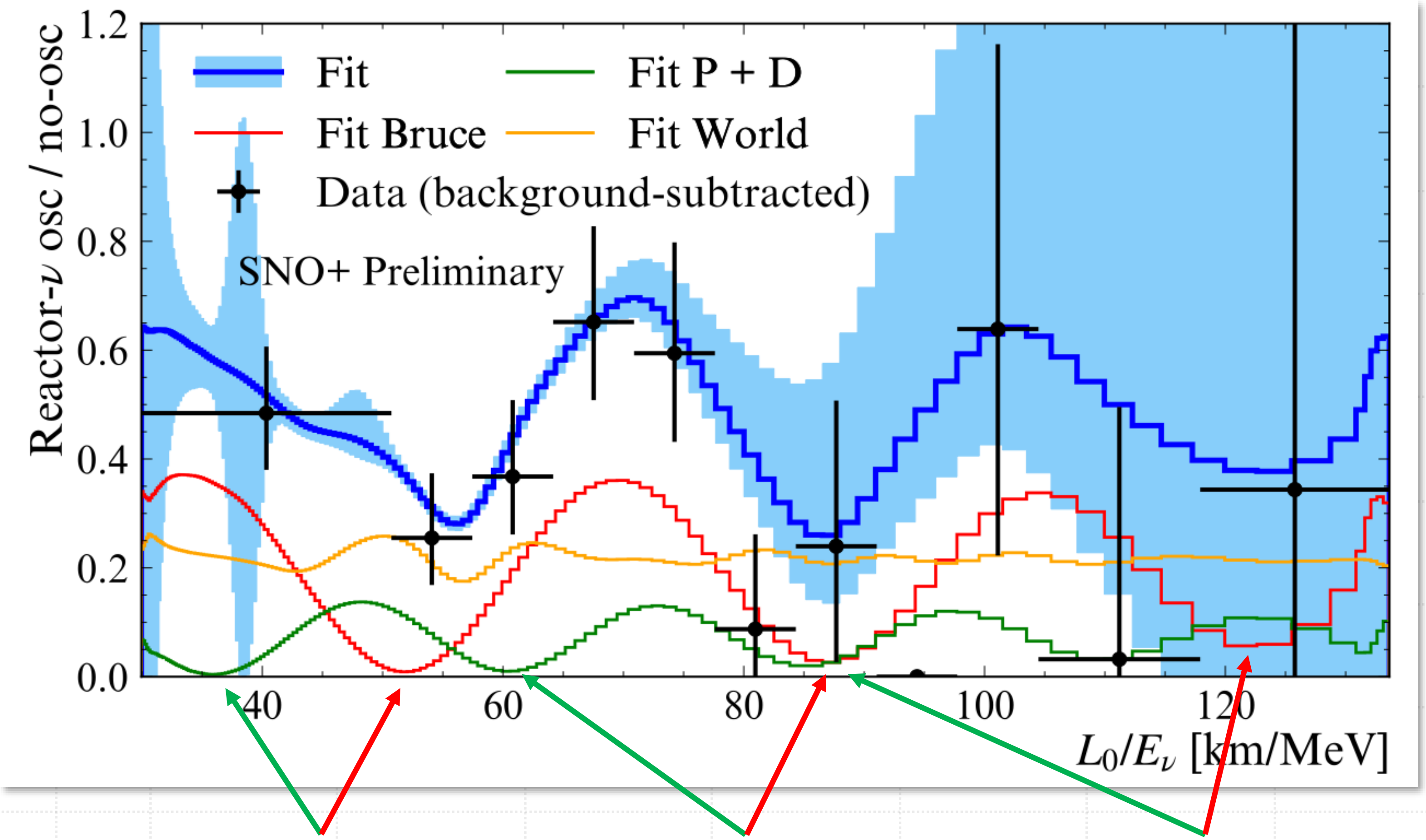


NuFit 6.1: Global Fit

Thank you to the SNO+ collaboration!

Backups

Oscillation Results

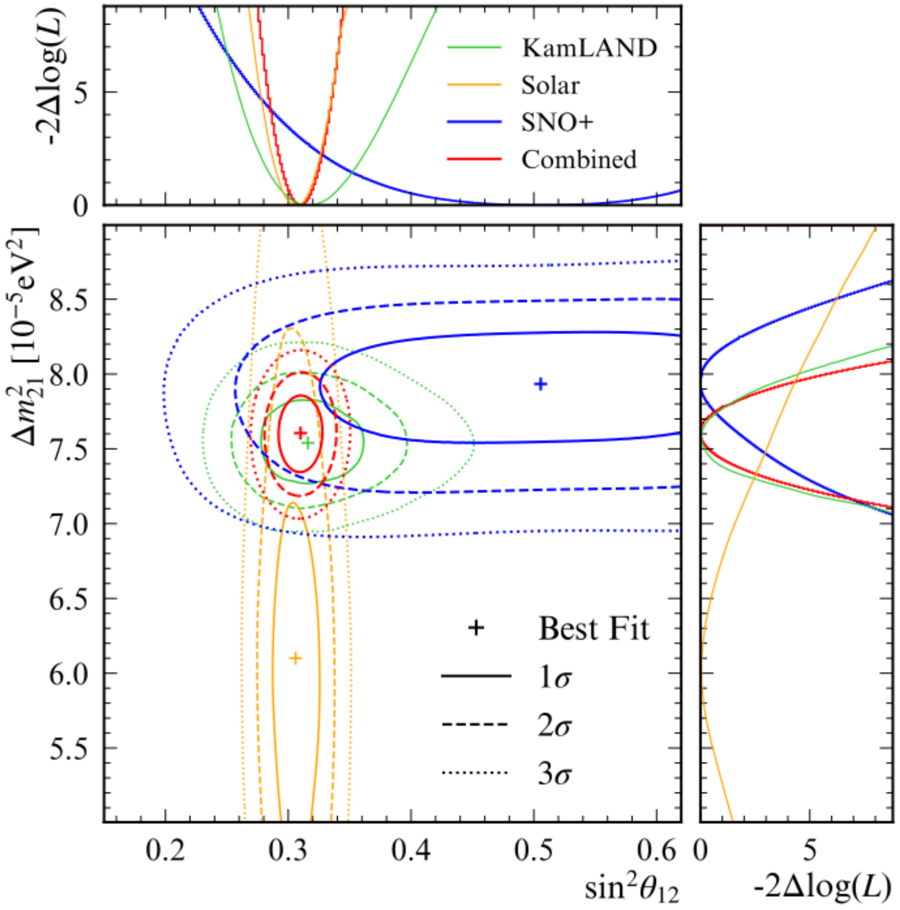


2nd oscillation peak 3rd oscillation peak 4th oscillation peak

- Ratio of reactor IBD spectrum with / without neutrino oscillation

JUNO Contours

SNO+ (Nov 18th)



JUNO (Nov 19th)

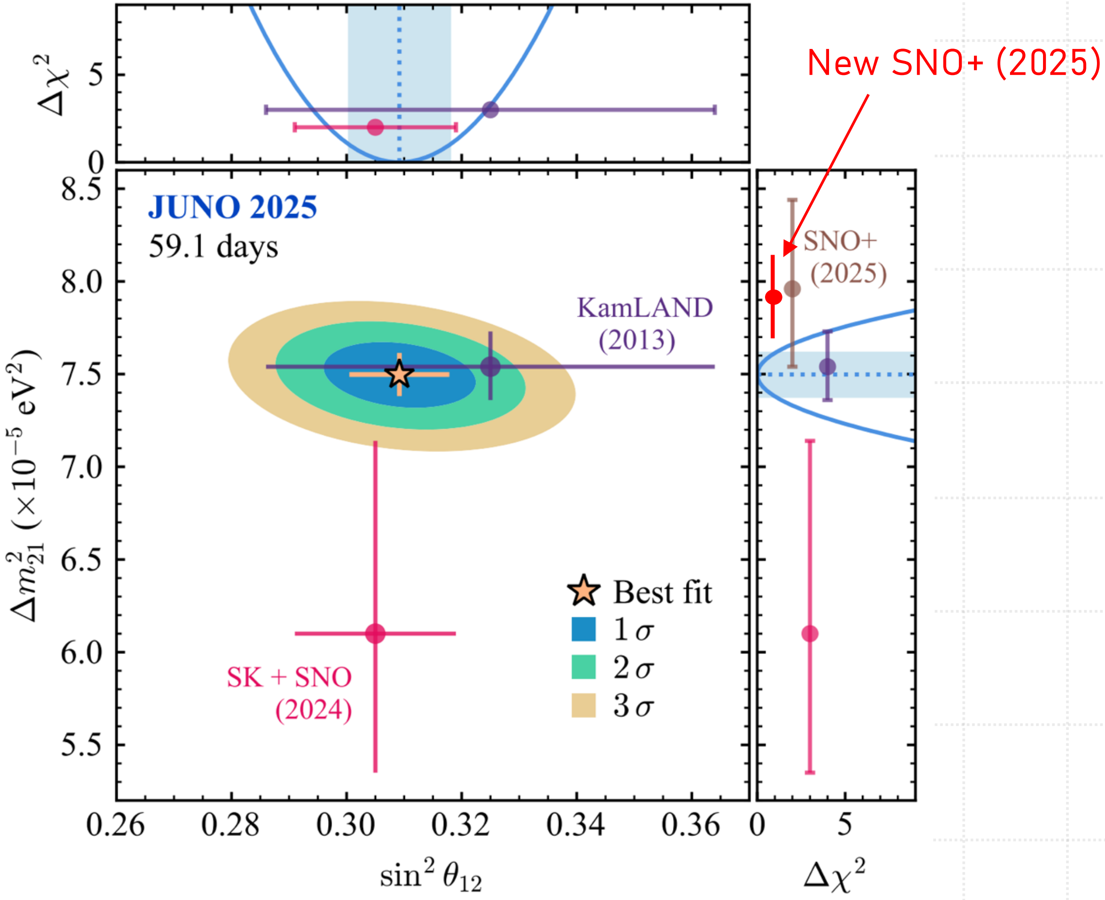
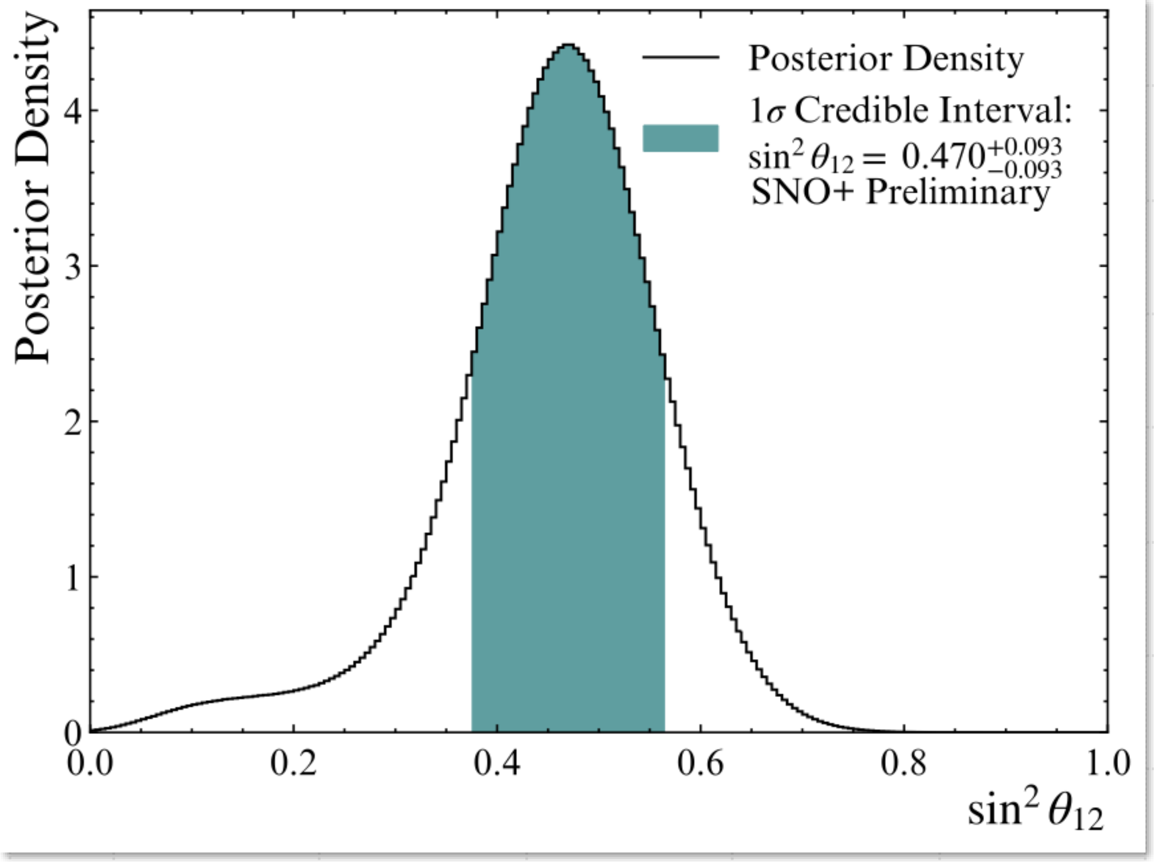
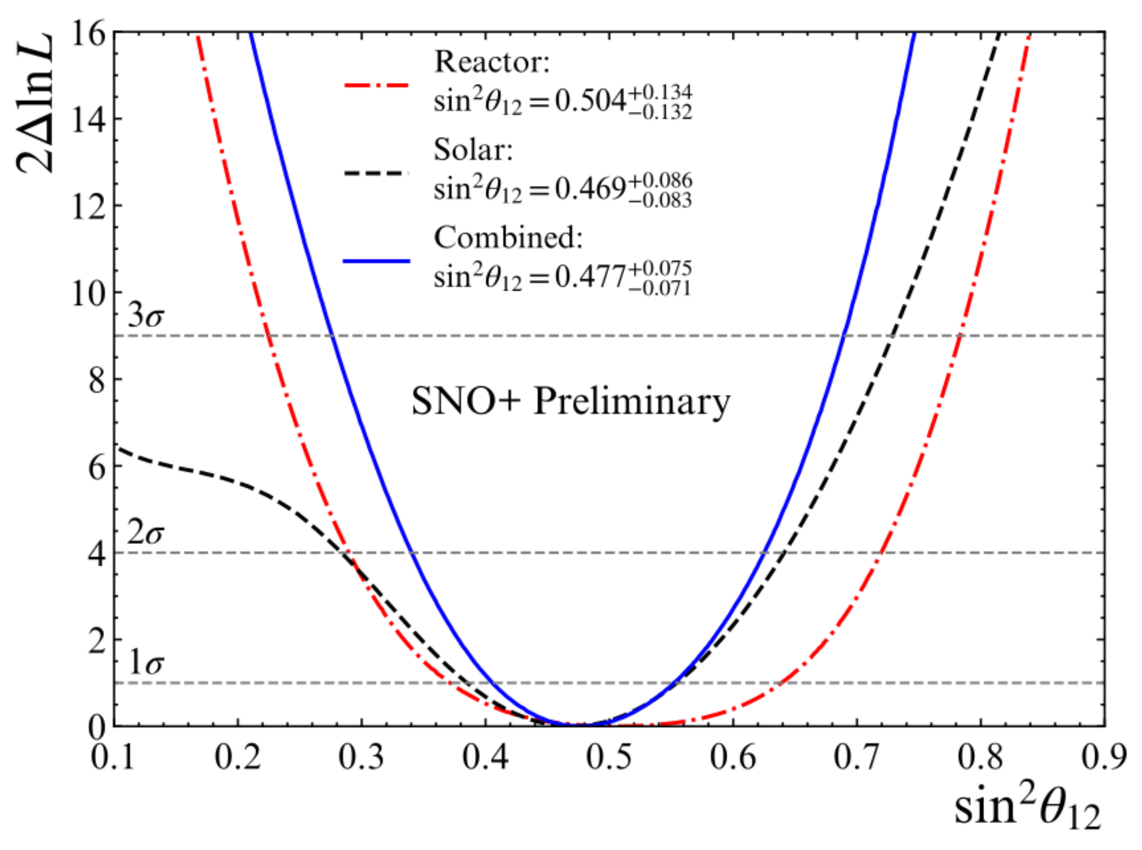


Figure adapted from https://arxiv.org/abs/2511.14593

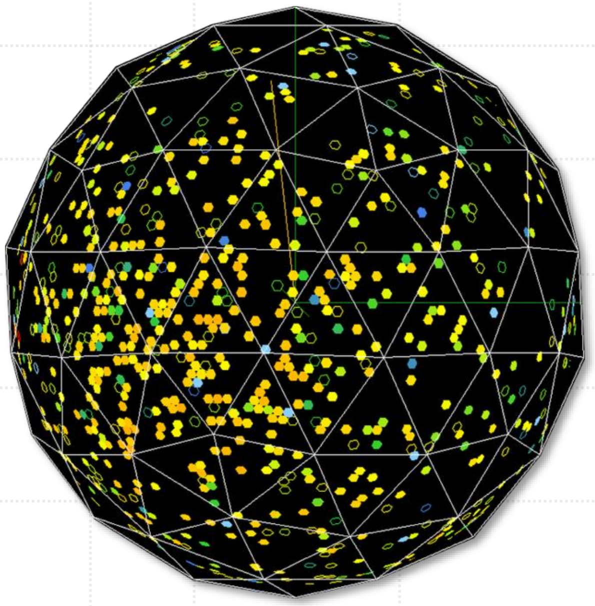
Solar Fit


Posterior Density
1σ Credible Interval:
$\sin^2\theta_{12} = 0.470^{+0.093}_{-0.093}$
SNO+ Preliminary
Posterior Density
$\sin^2\theta_{12}$


Reactor:
$\sin^2\theta_{12} = 0.504^{+0.134}_{-0.132}$
Solar:
$\sin^2\theta_{12} = 0.469^{+0.086}_{-0.083}$
Combined:
$\sin^2\theta_{12} = 0.477^{+0.075}_{-0.071}$
SNO+ Preliminary
$2\Delta\ln L$
3σ
2σ
1σ
$\sin^2\theta_{12}$

Event Reconstruction

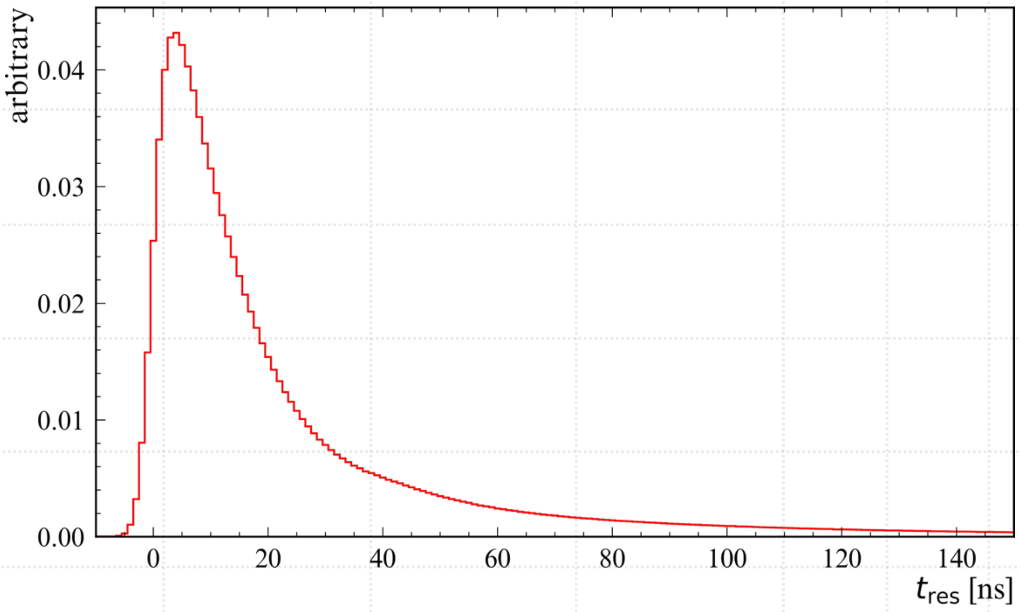
- Charged particles excite the liquid scintillator
- Liquid scintillator emits light isotropically
- Only use number of PMT hits (N_{hit}) and relative timing/position of these:



Reconstruction:
- $N_{hit} \propto E$ (roughly).
- Event t and $\vec{r}$ are fitted.

Pulse shape (time residual plot):
- $t_{res} = t_{PMT\ hit} - t - t_{TOF}(\vec{r})$

Example Pulse Shape PDF:



Use these to identify physical processes!

Geo-Neutrinos

- These geo-$\bar{\nu}_e$ also lead to IBDs.
- Spectrum overlaps with lower energy reactor $\bar{\nu}_e$.

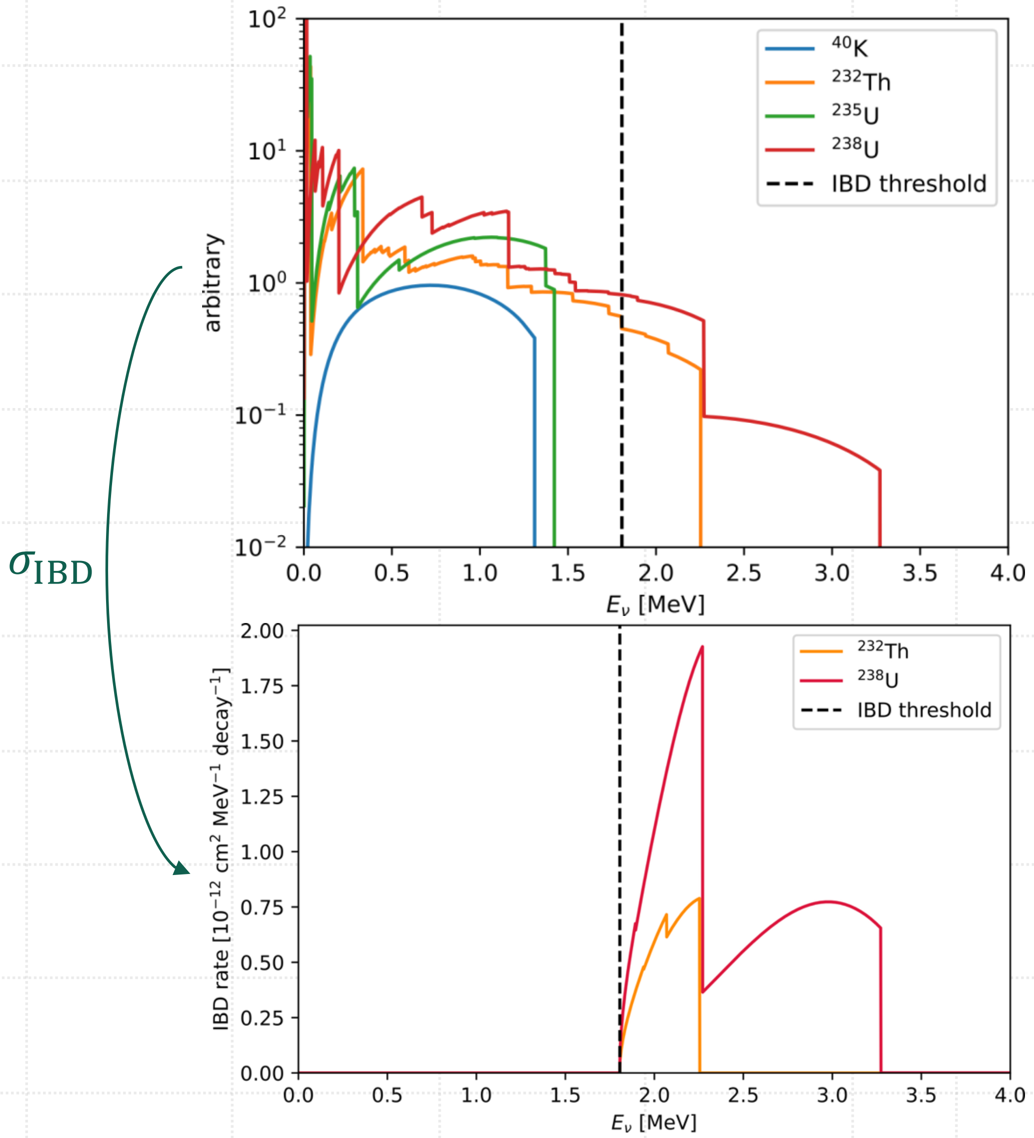
➡ Effectively **fit the geo-ν flux simultaneously**.

- Oscillation integrated over "large" distances:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx s_{13}^4 + c_{13}^4(1 - 2s_{12}^2 c_{12}^2) \approx 0.55$$

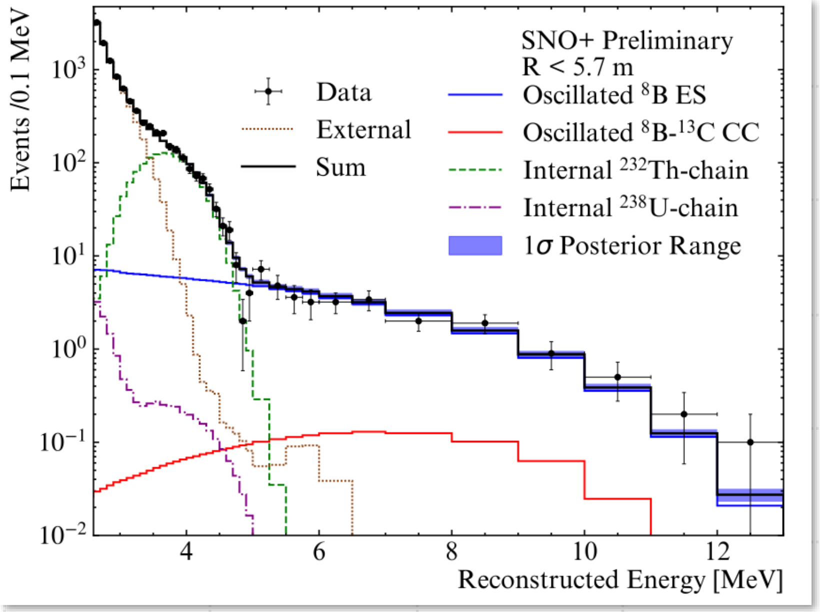
- U/Th ratio loosely constrained from geology:

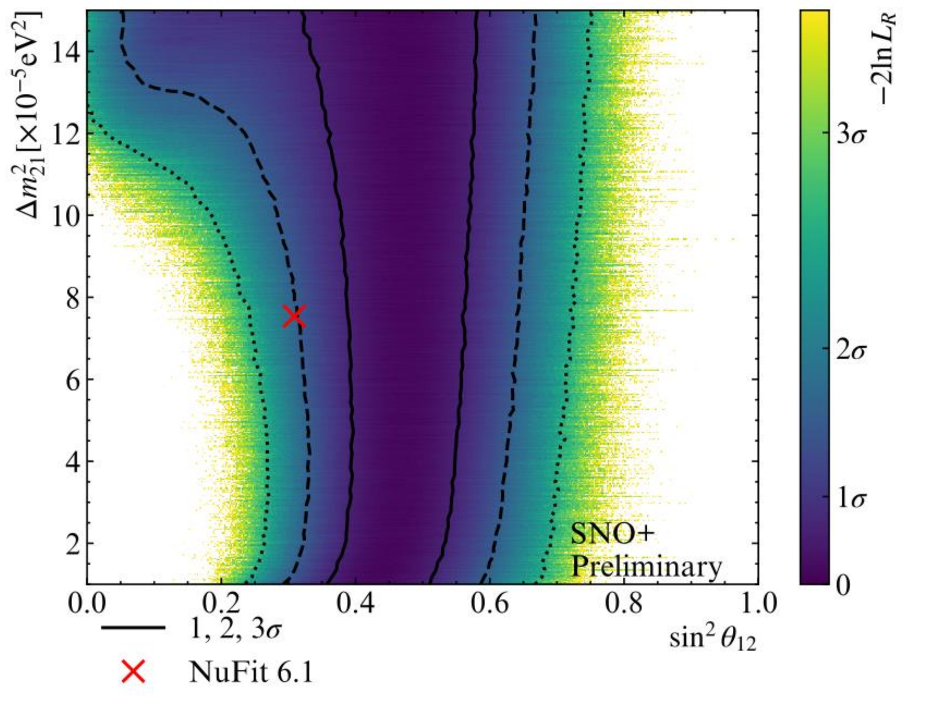
$$R_{\mathrm{U/Th}} = 3.7 \pm 1.3$$



Solar Neutrinos

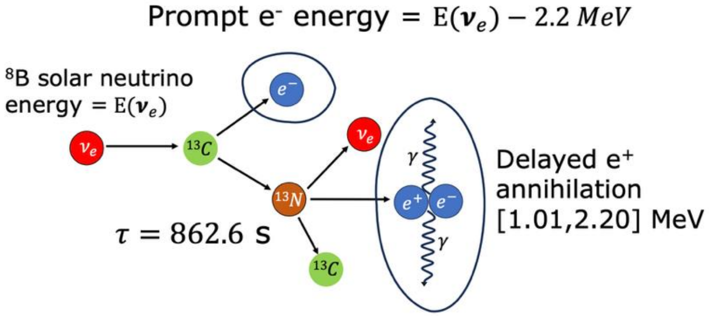
- ^{8}B ν ES on e^{-}:

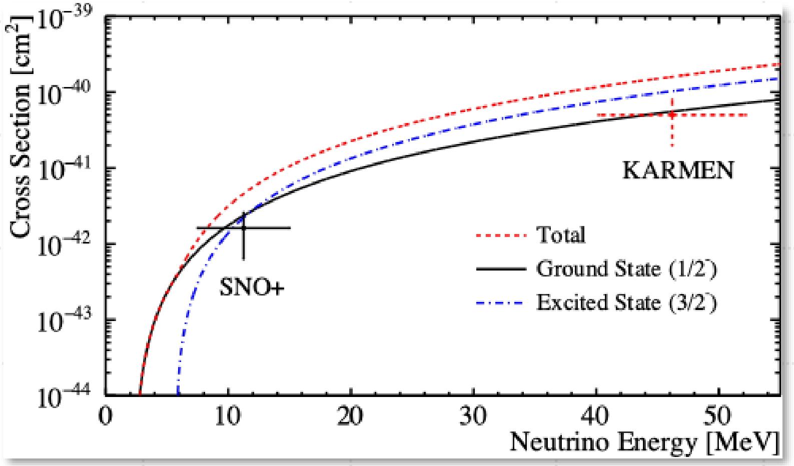




- ^{8}B ν_e CC interaction on ^{13}C:

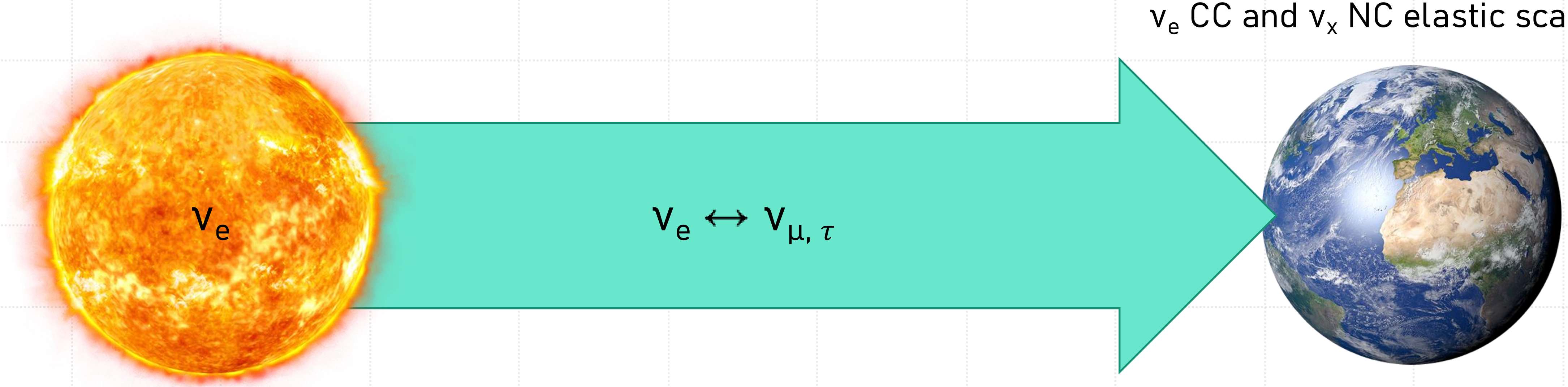
(not previously measured)

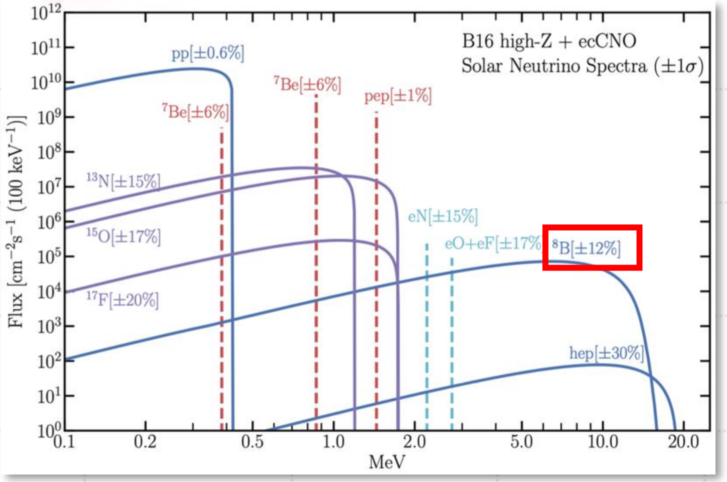


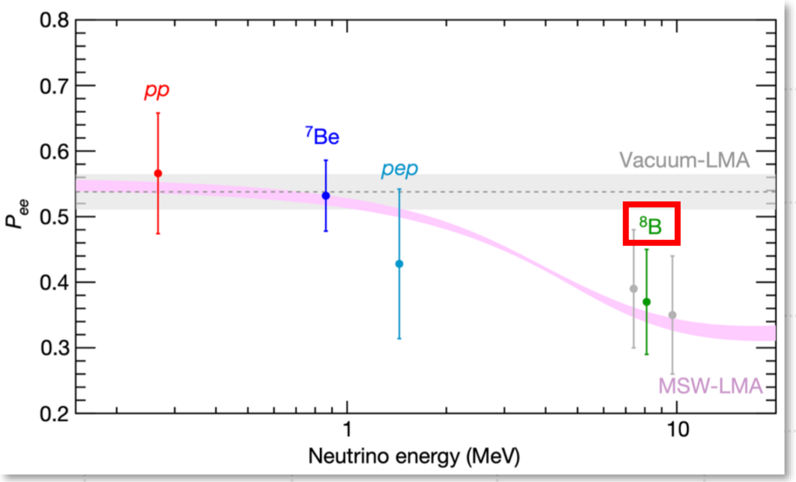


Solar Neutrinos

ν_e CC and ν_x NC elastic scattering



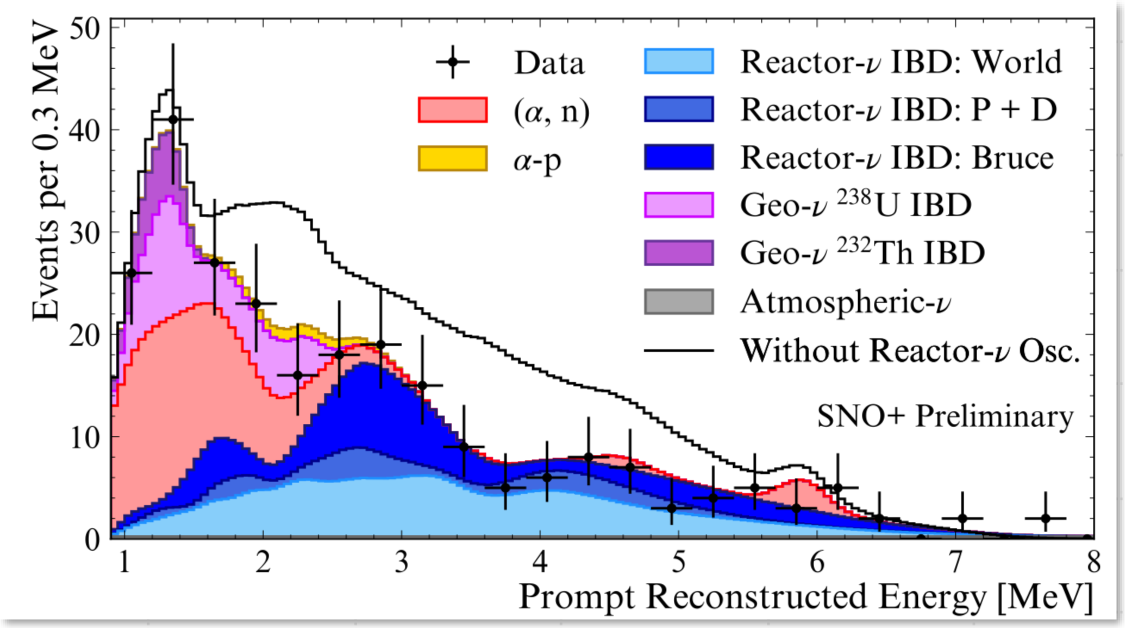




Geo-ν Results

Cut & re-fit:

$\Phi_{geo} = 49^{+13}_{-12}$ TNU



↓ (α, n)-IBD cut below 3.5 MeV ↓