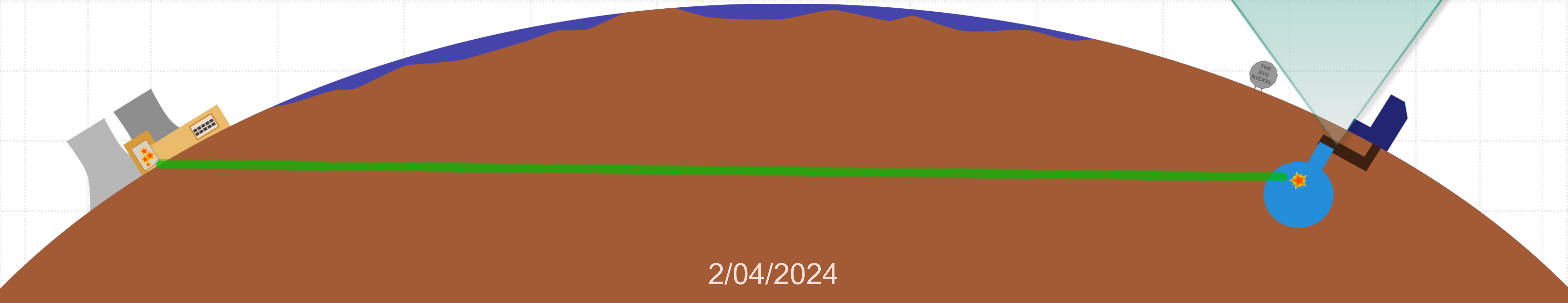
Measuring Reactor Antineutrino Oscillation at SNO+

SNO+

UNIVERSITY OF SUSSEX

James Page



2/04/2024

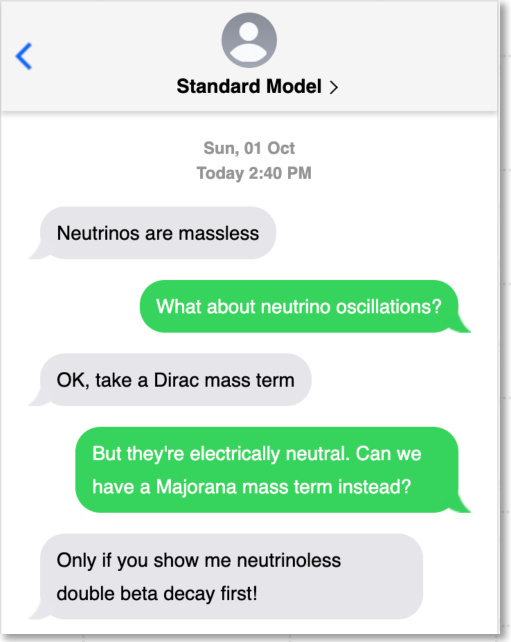
Contents

The SNO+ Experiment

The Motivation

Want to detect neutrinoless double beta decay (0νββ), to test whether neutrinos are Majorana fermions.

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$



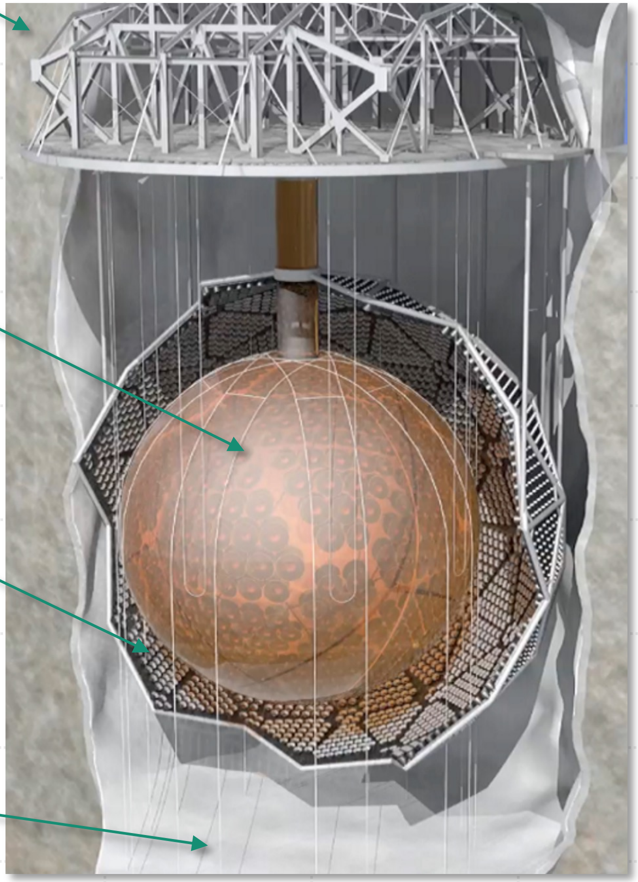
The Detector

2 km overburden

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

Over 9000 PMTs + outward looking PMTs

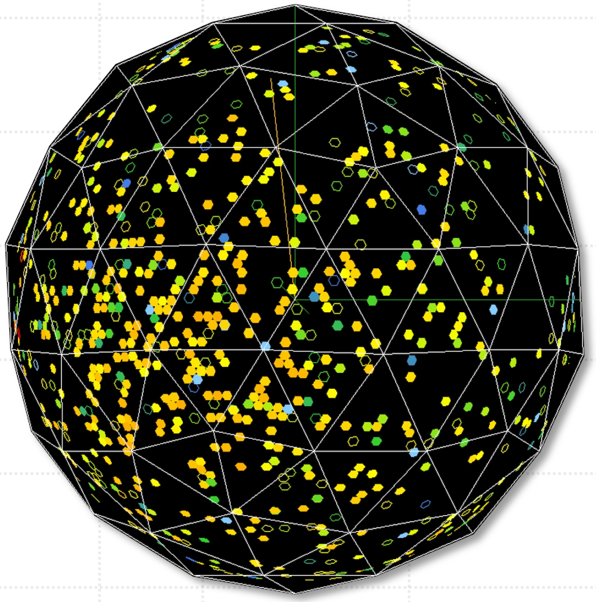
Surrounded by ultra-pure water



- Based on the Sudbury Neutrino Observatory (SNO) 
- Ultra low radioactive and cosmogenic backgrounds
- Load ^{130}Te to produce 0νββ!

The SNO+ Experiment

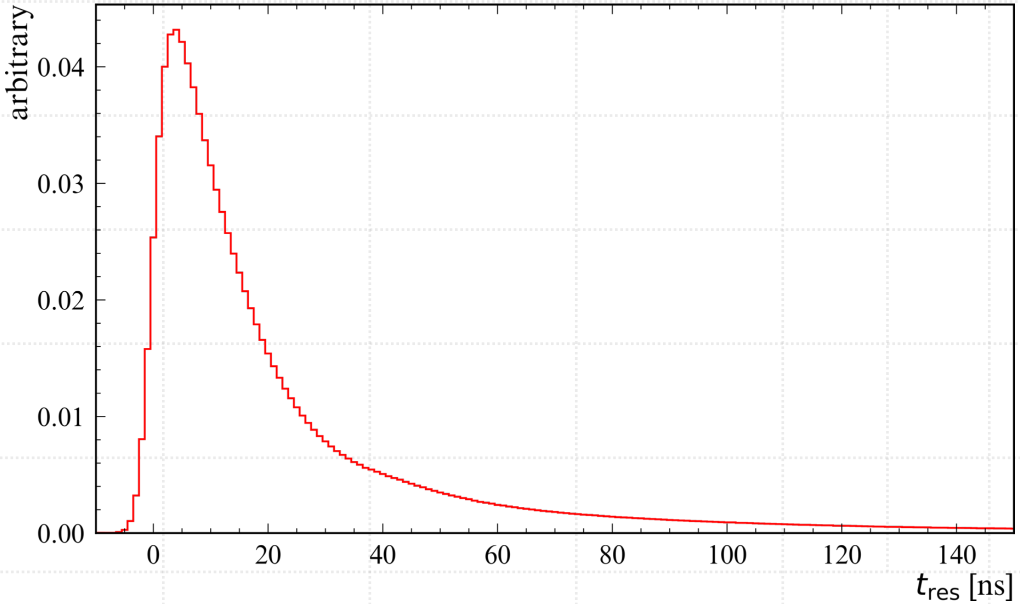
- Liquid scintillator provides almost no directionality information.
- Only use number of PMT hits (nhit) and relative timing/position of these:



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

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

Example Pulse Shape PDF:



Use these to identify physical processes!

Why Reactor Antineutrinos?

Physics Goal Selection

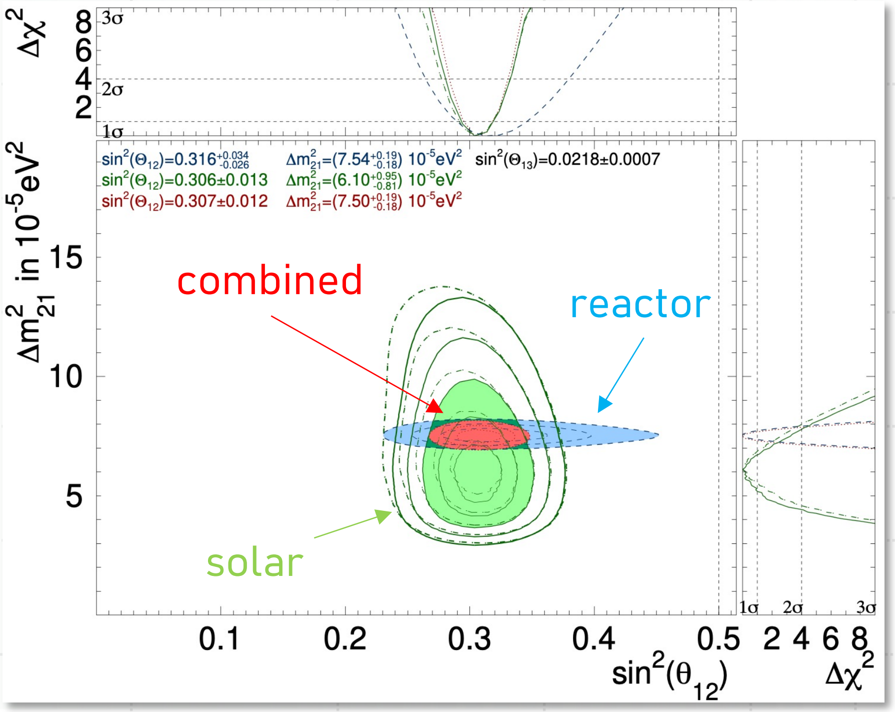
- Neutrinoless double ★ beta decay ★
- **Reactor antineutrinos**
- Geo-neutrinos
- Solar neutrinos
- SNEWS
- Invisible nucleon decay

- Nuclear reactors provide the greatest source of MeV-scale antineutrinos which SNO+ is sensitive to (1 – 10 MeV).

- **Study neutrino oscillation:**
  - $\bar{\nu}_e$ survival probability.
  - Long baseline experiment.
  - Current ~**1.5σ tension** between **solar** and **reactor** fits:

+ First reactor antineutrino detection in water!
Published last year [1]

[2]



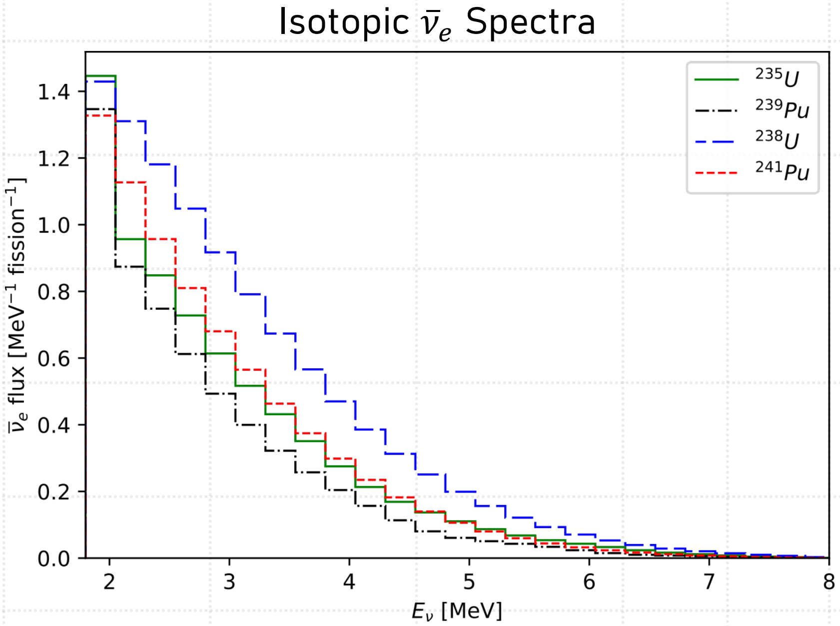
[1] A. Allega *et al.* (SNO+ Collaboration), "Evidence of antineutrinos from distant reactors using pure water at SNO+" Phys. Rev. Lett. 130, 091801 (2023)
[2] K. Abe et al. (Super-Kamiokande), 2024 [arXiv:2312.12907 [hep-ex]].

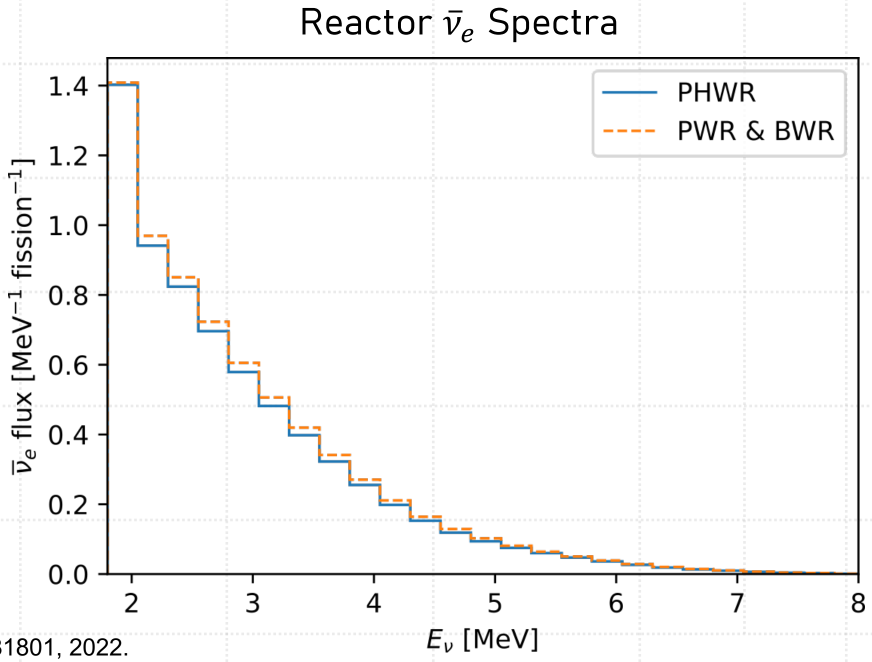
Antineutrino Production

- Emitted flux primarily comes from **β-decay of 4 isotopes**: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
- Each has its own spectrum, from [1-3].
- **Simulate 3 reactor types**, with different fission fractions of these isotopes:

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

- Combine with reactor thermal power outputs, and average energy emitted per fission, to get **$\bar{\nu}_e$ flux [MeV^{-1} · s^{-1}]**.

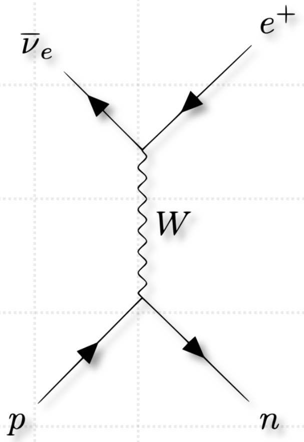


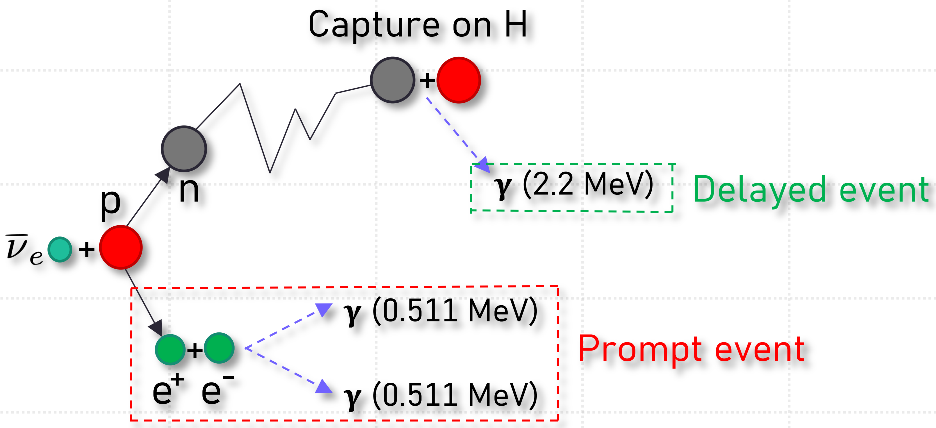


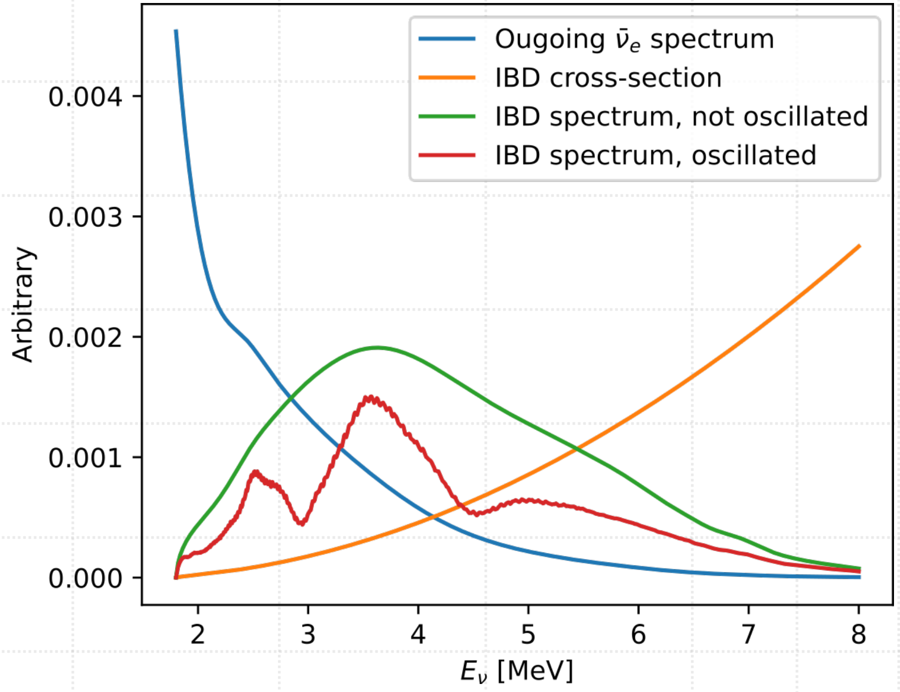
[1] Add Huber paper
[2] Add Mueller paper.
[3] FP An, et al. Joint determination of reactor antineutrino spectra from u 235 and pu239 fission by daya bay and prospect. Physical review letters, 128(8):081801, 2022.

Antineutrino Detection

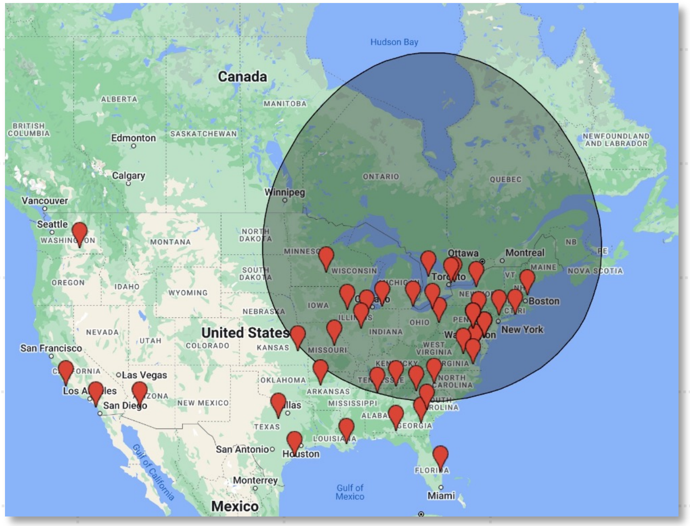
Primarily detectable via Inverse Beta Decay (IBD):







- Δt ~ 200μs
- Tagging and various cuts (Δt, Δr, E, etc) removes **most** backgrounds.



Oscillation:

- >60% of flux from the 3 reactor complexes in Ontario.
- SNO+ is 240 to 350 km from from these.

Sensitive to Δm_{21}^2 and θ_{12} (long baseline experiment).

Background: Geo-Neutrinos

- Produced from radioactive decays in the Earth.
- Geo-ν IBDs are indistinguishable from reactor ones.
- A lot of uncertainty, depending on the Earth model.

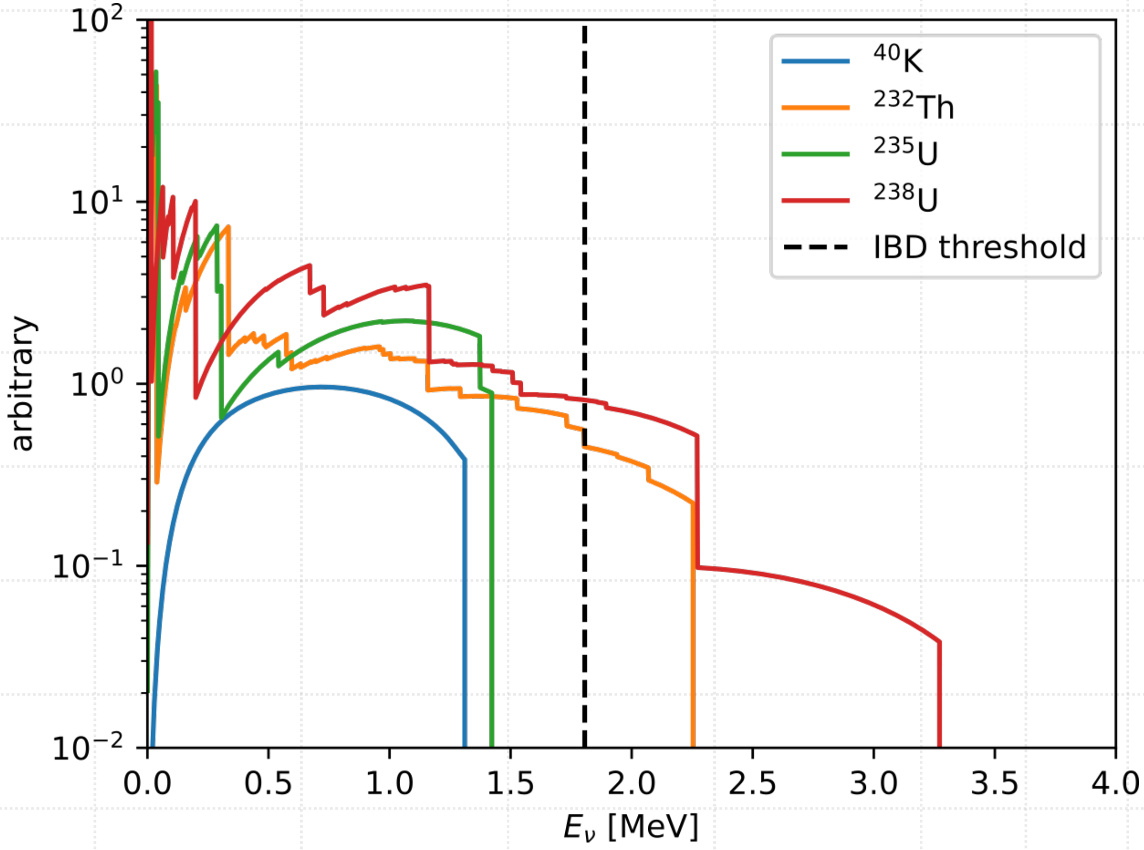
➡ Effectively fit the geo-ν flux simultaneously.

- Oscillation averaged out over all distances:

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

➡ Almost only depends on θ_{12}.

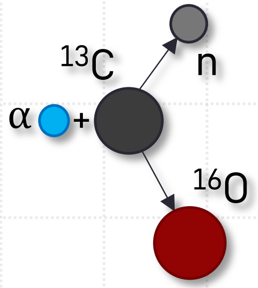
Non-negligible geologic sources of $\bar{\nu}_e$, normalisations undetermined [1]



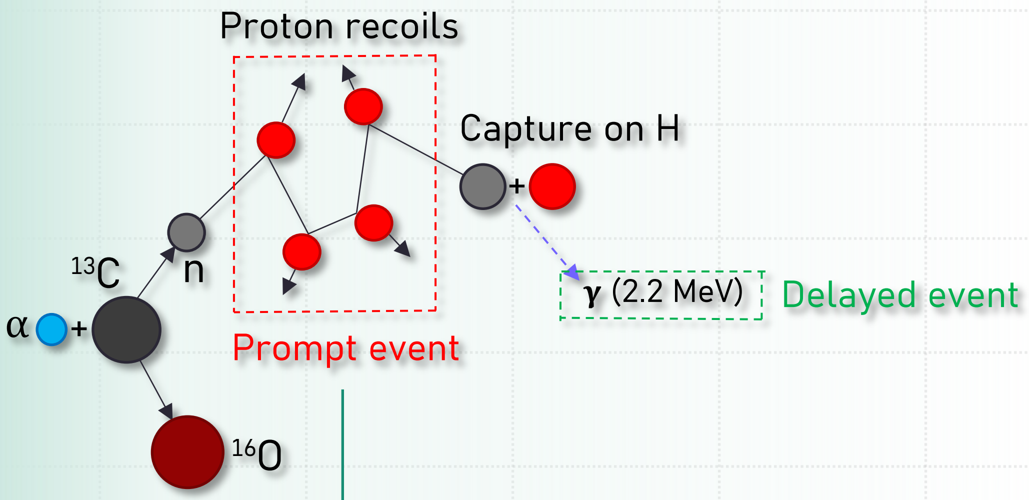
[1] https://www.awa.tohoku.ac.jp/~sanshiro/research/geoneutrino/spectrum/

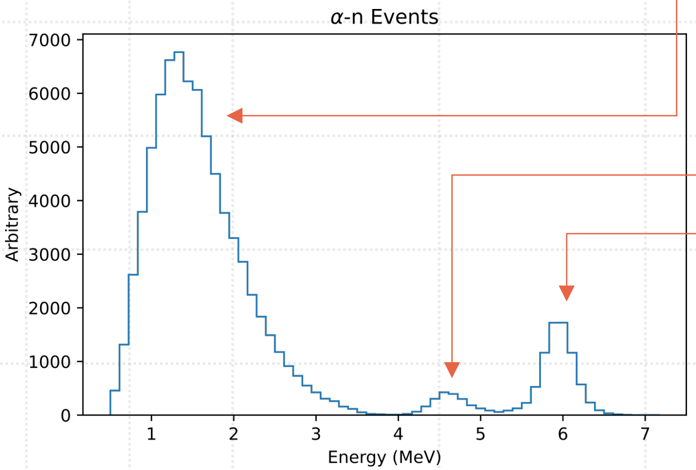
Background: (α, n) Events

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



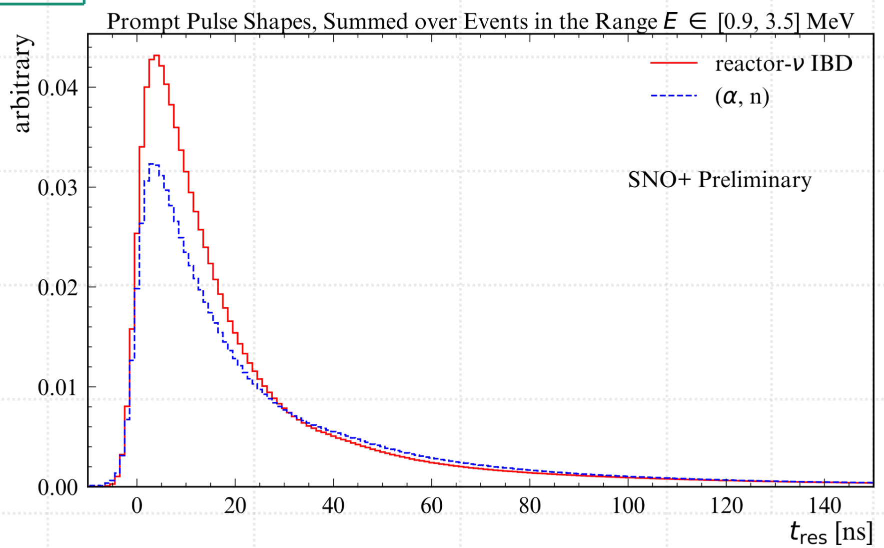
$^{13}C(\alpha\text{-}n)^{16}O$ prompt events	
GS ^{16}O	**Proton recoil**
	^{12}C scattering
ES ^{16}O	^{16}O deexcitation





longer process & different scintillator response

different pulse shape:

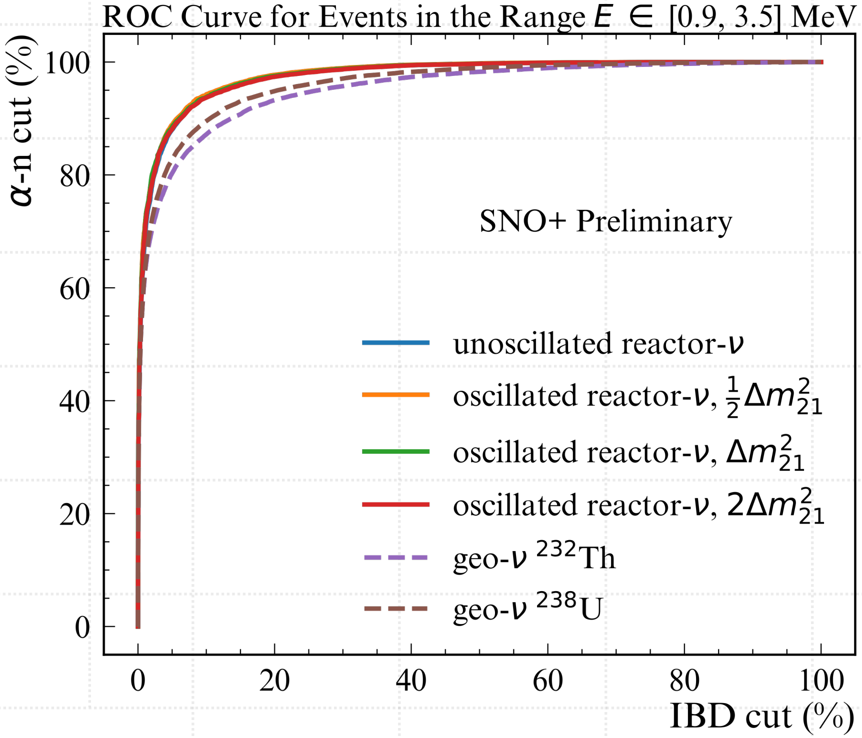


(α, n) vs IBD Classifier

Pulse shapes are **correlated** with the event's reconstructed energy **E** and radial position **R**:

Use a **Fisher discriminant** based classifier to capture this:

- Treat each bin t_i as a dimension.
- **Add R as an extra dimension**.

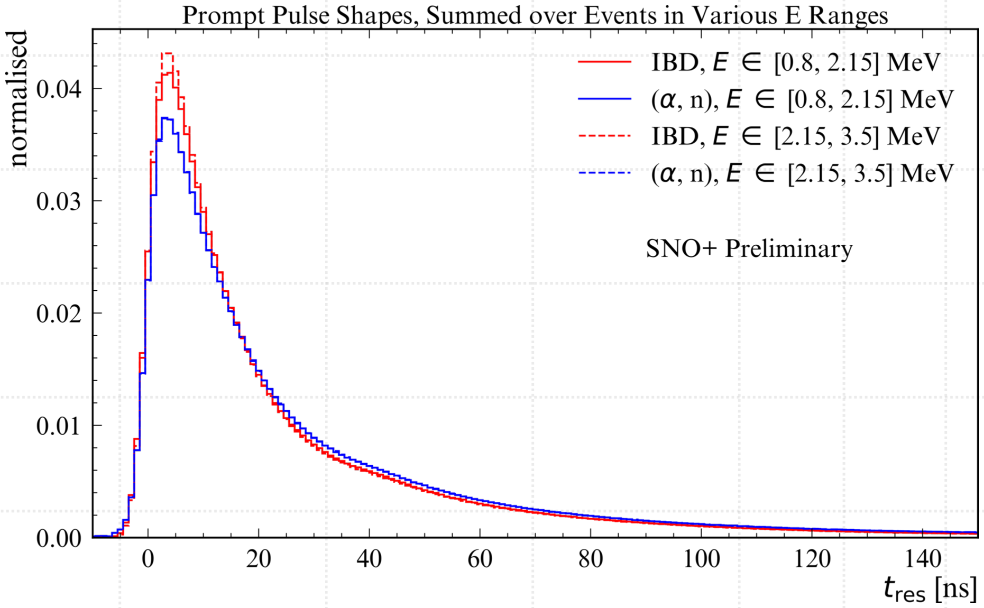


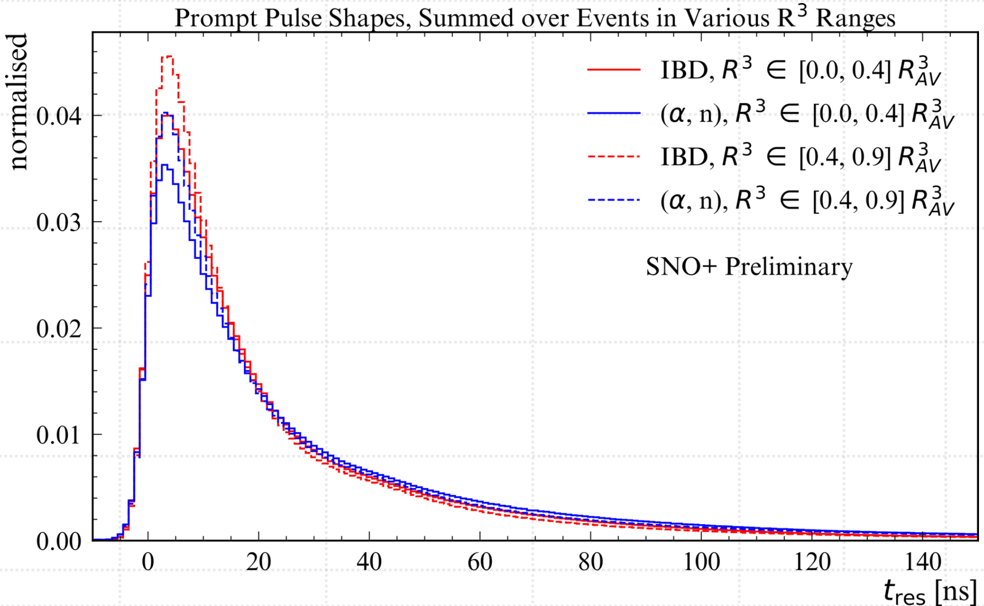
Events sampled from expected (α, n) and various IBD distributions.

All events obey:
- $E \in [0.9, 3.5]$ MeV
- $R^3 < 0.9\, R_{AV}^3$

R_{AV} = radial position of acrylic vessel

Events sampled from uniform E and R^3 distributions:



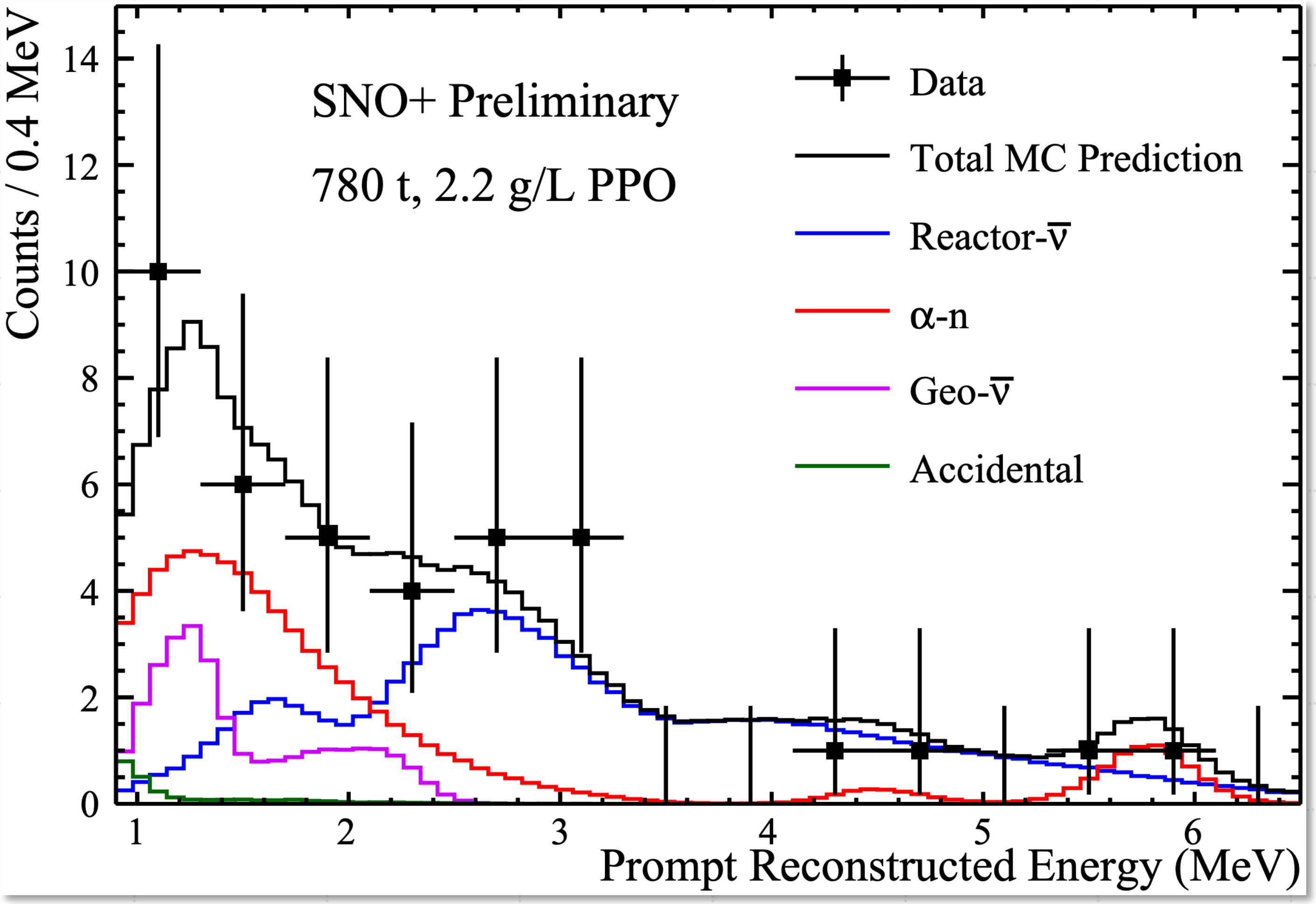


Prompt Energy Spectrum

Putting this signal and these backgrounds together, get total MC prediction.

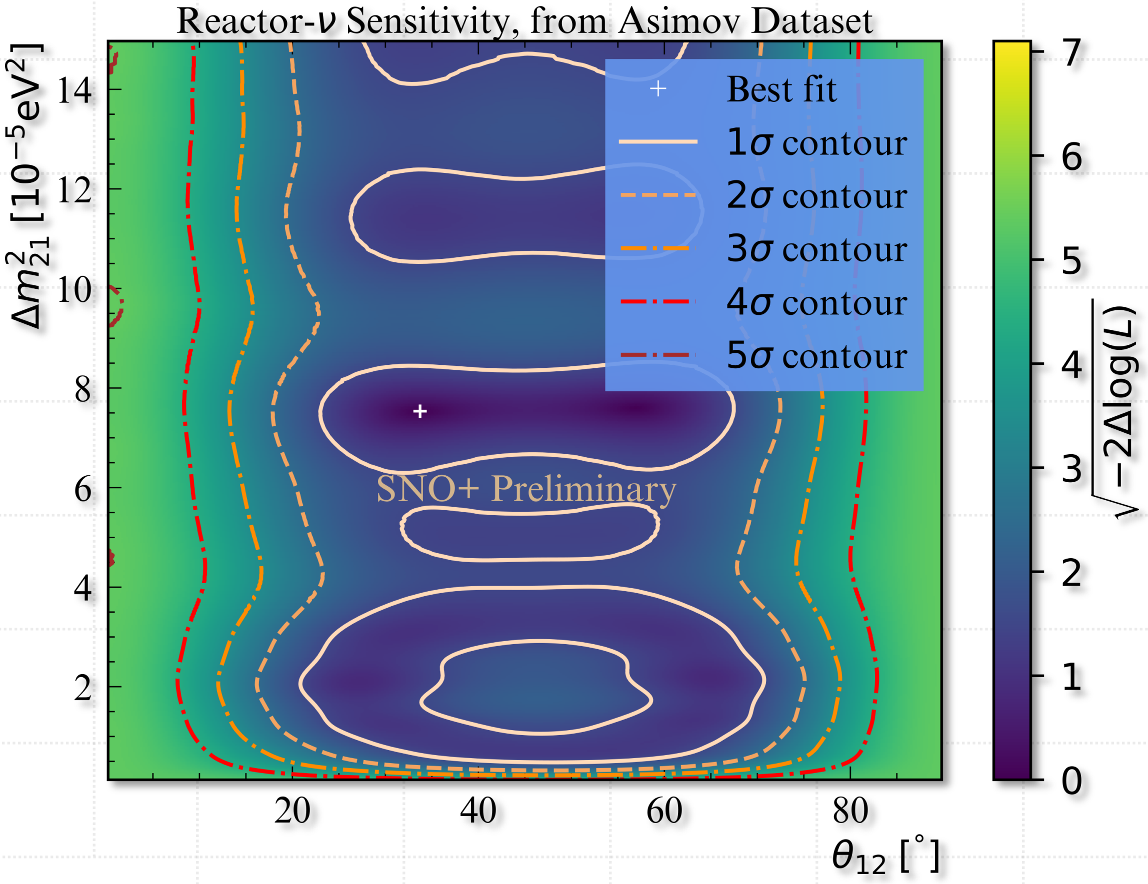
Compare to data, using the same cuts.

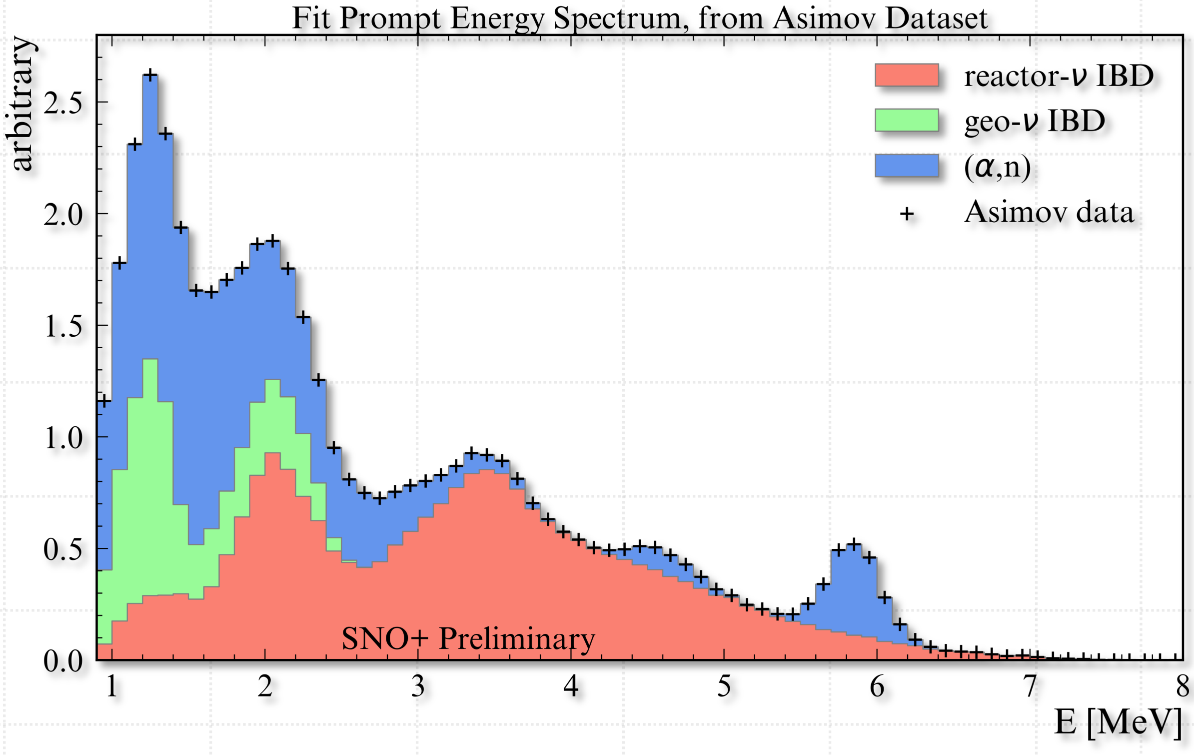
Example Data–MC comparison (<100 days of livetime, no classifier):



Oscillation Fit

- Compute reactor and background PDFs (no oscillation).
- Construct **Asimov dataset**, with $\Delta m_{21}^2 = 7.53 \times 10^{-5}$ eV^2 and $\theta_{12} = 33.6°$.
- Fit PDFs:

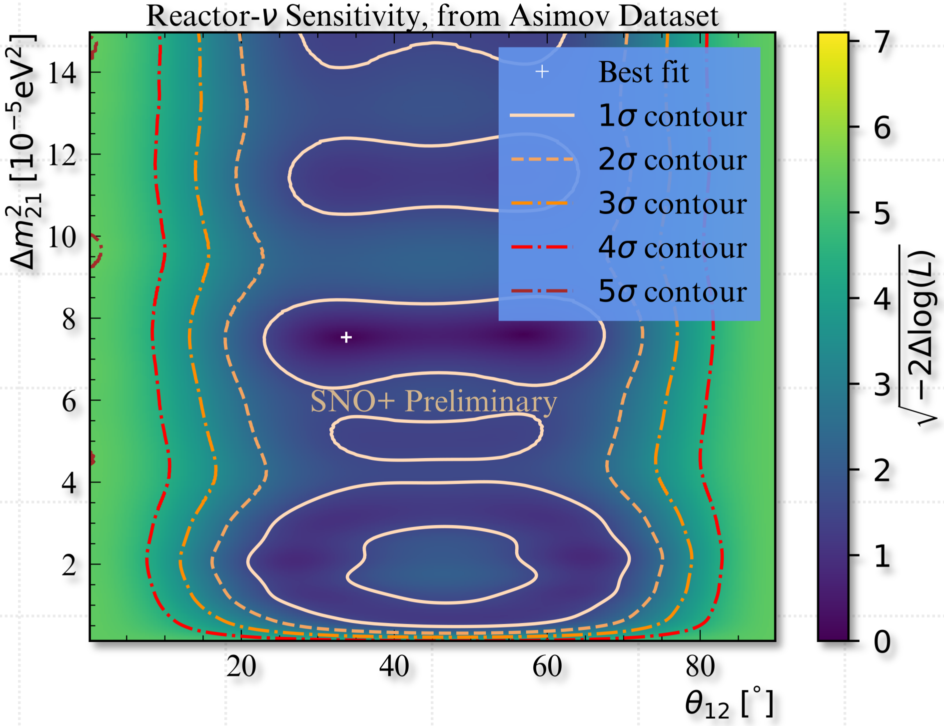


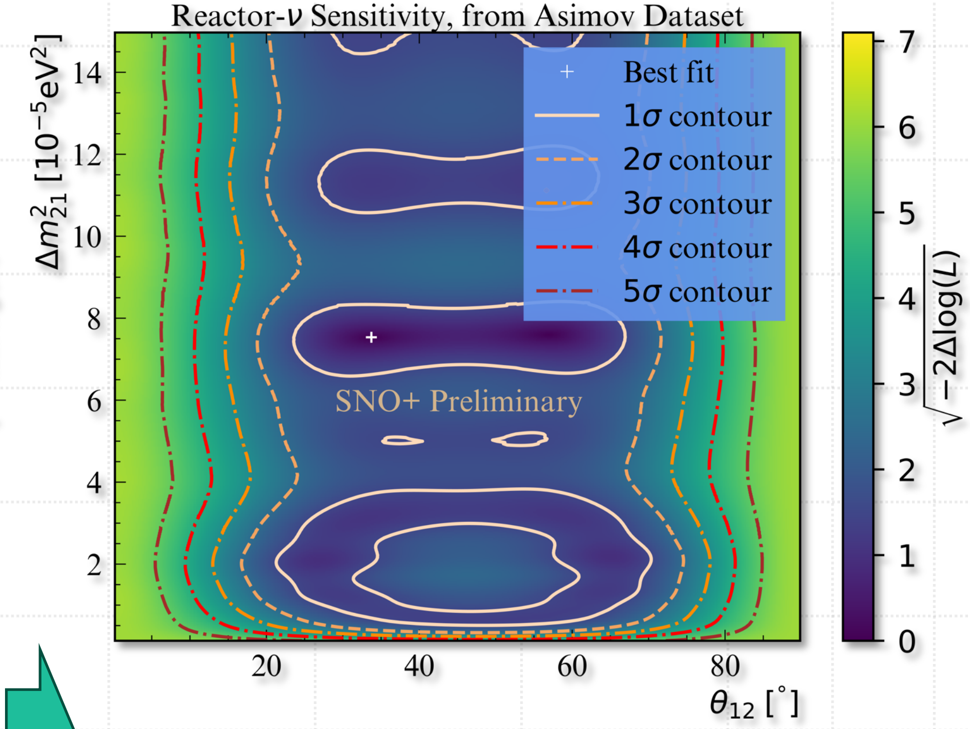


Fit values: $\Delta m_{21}^2 = 7.54^{+0.52}_{-0.61} \times 10^{-5}$ eV^2, $\theta_{12} = (33^{+31}_{-8})°$

Oscillation Fit

Impact of the classifier.





Without Classifier:

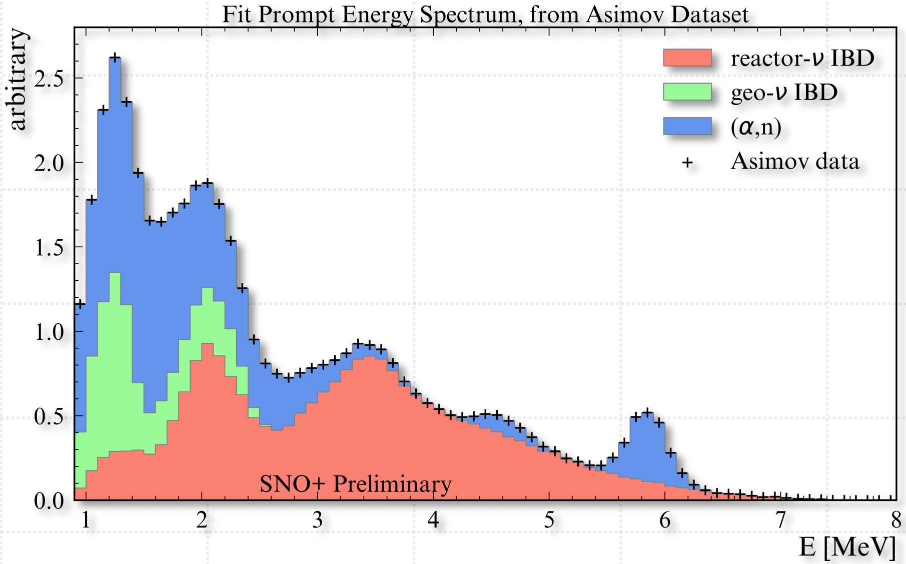
$\Delta m_{21}{}^2 = 7.54^{+0.52}_{-0.61} \times 10^{-5}$ eV^2

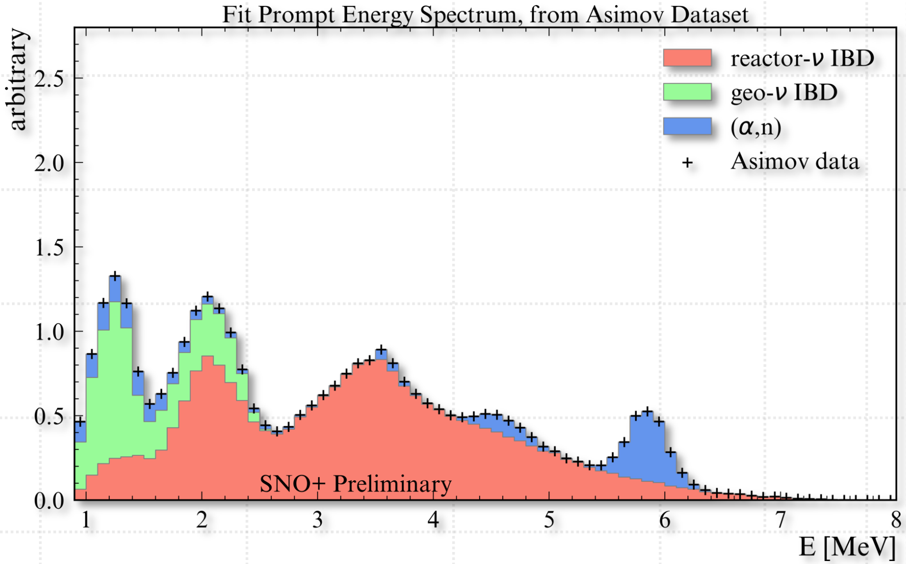
$\theta_{12} = (33^{+31}_{-8})°$

With Classifier:

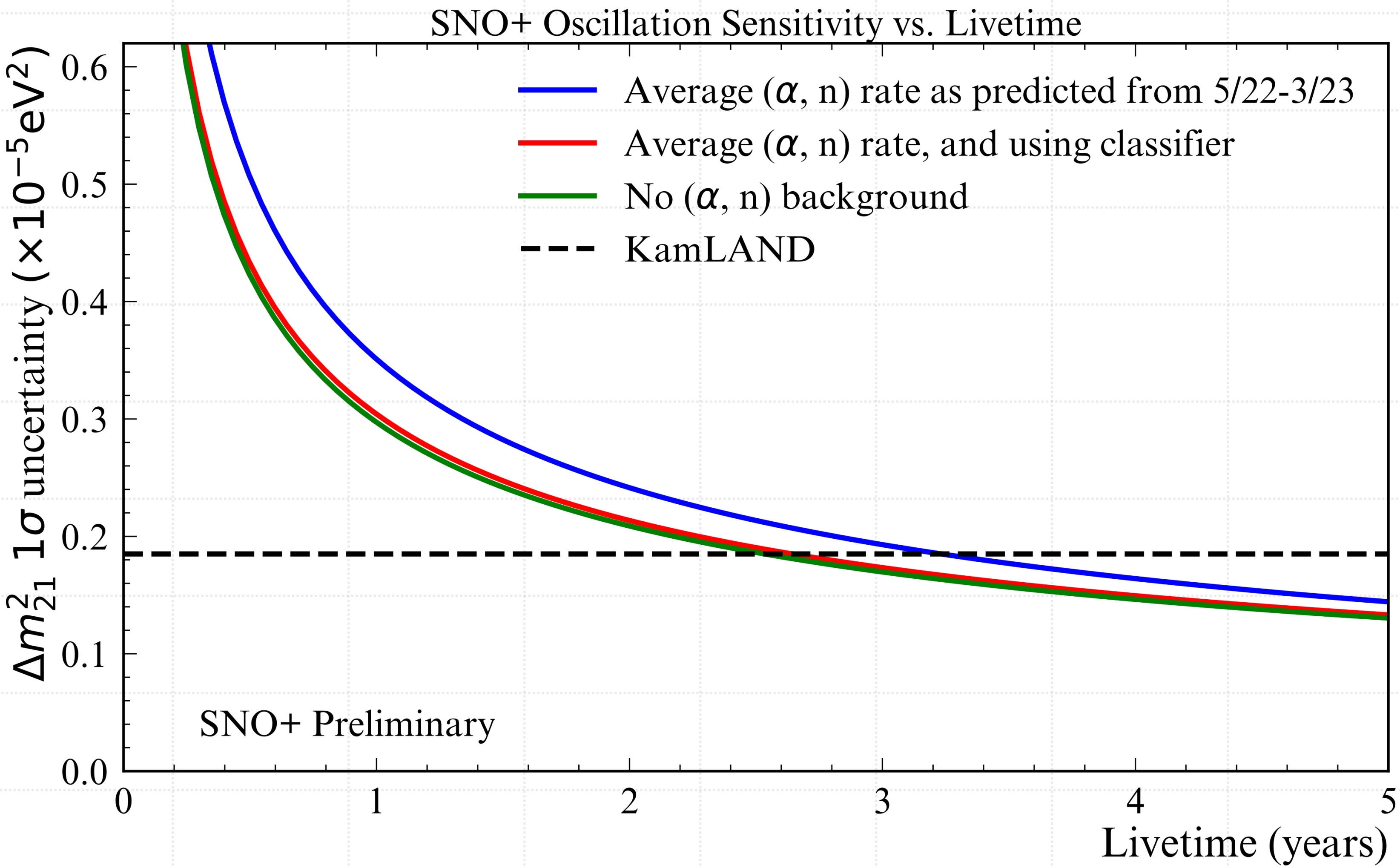
$\Delta m_{21}{}^2 = 7.54^{+0.46}_{-0.55} \times 10^{-5}$ eV^2

$\theta_{12} = (34^{+31}_{-7})°$



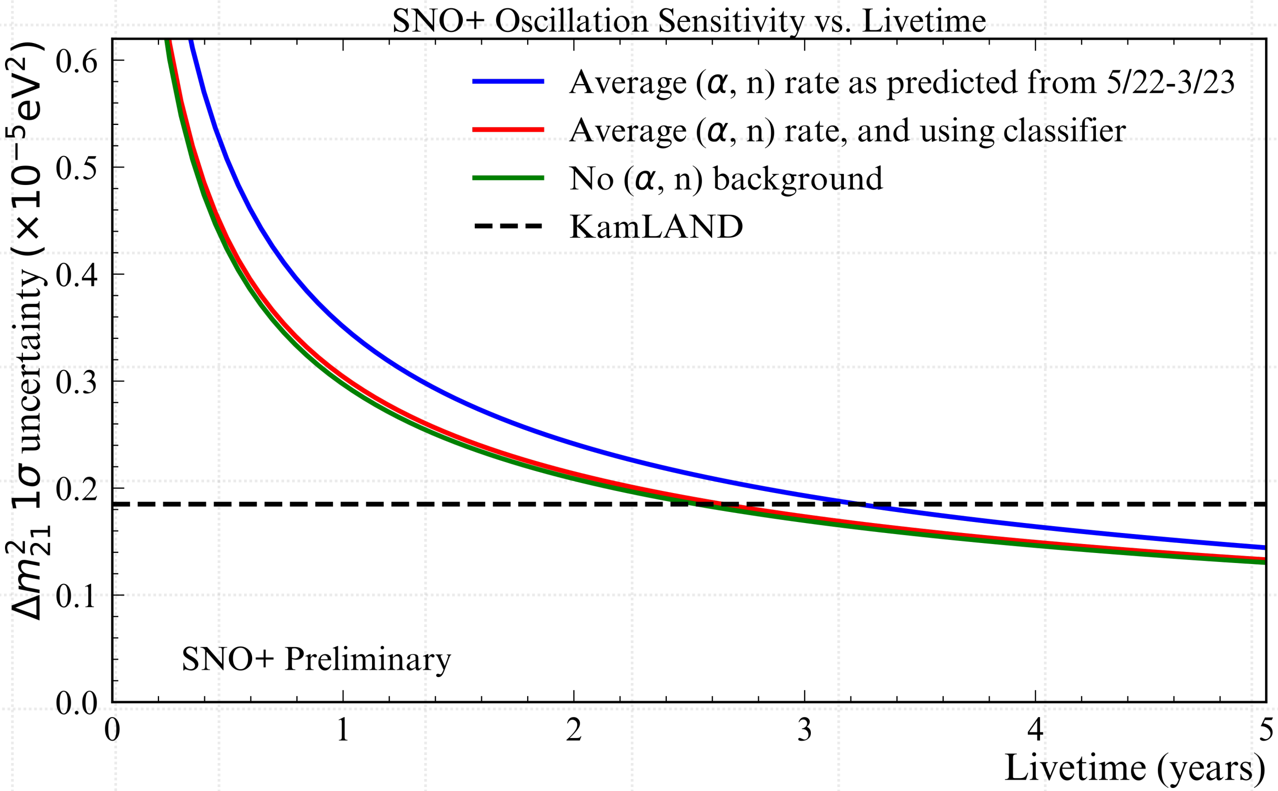


Sensitivity Over Time



Conclusion

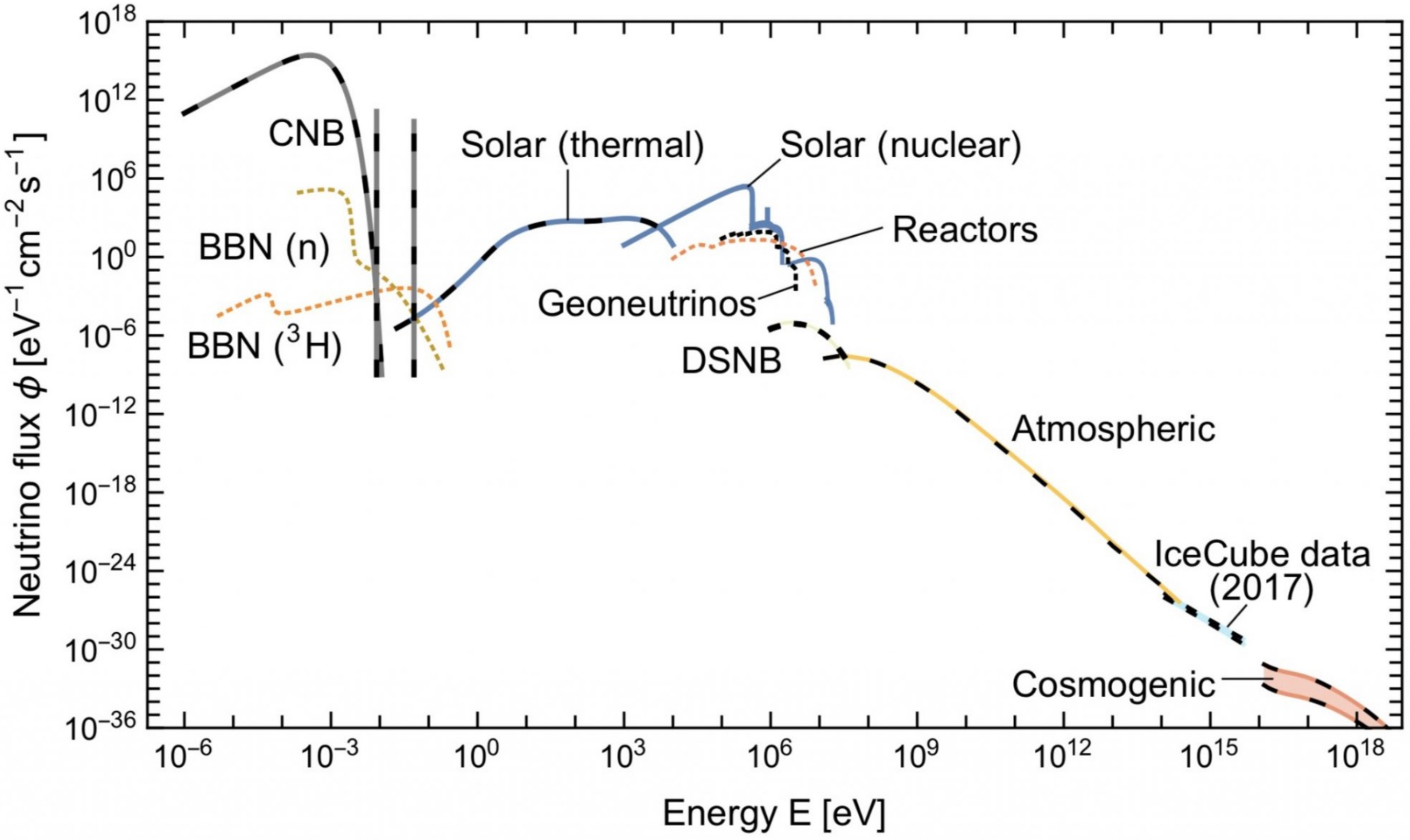
A competitive measurement is coming!



Big thanks to the SNO+ Collaboration!

Backup Slides

Grand Unified Neutrino Spectrum



Vitagliano, Edoardo, Irene Tamborra, and Georg Raffelt. "Grand unified neutrino spectrum at Earth: Sources and spectral components." *Reviews of Modern Physics* 92.4 (2020): 045006.