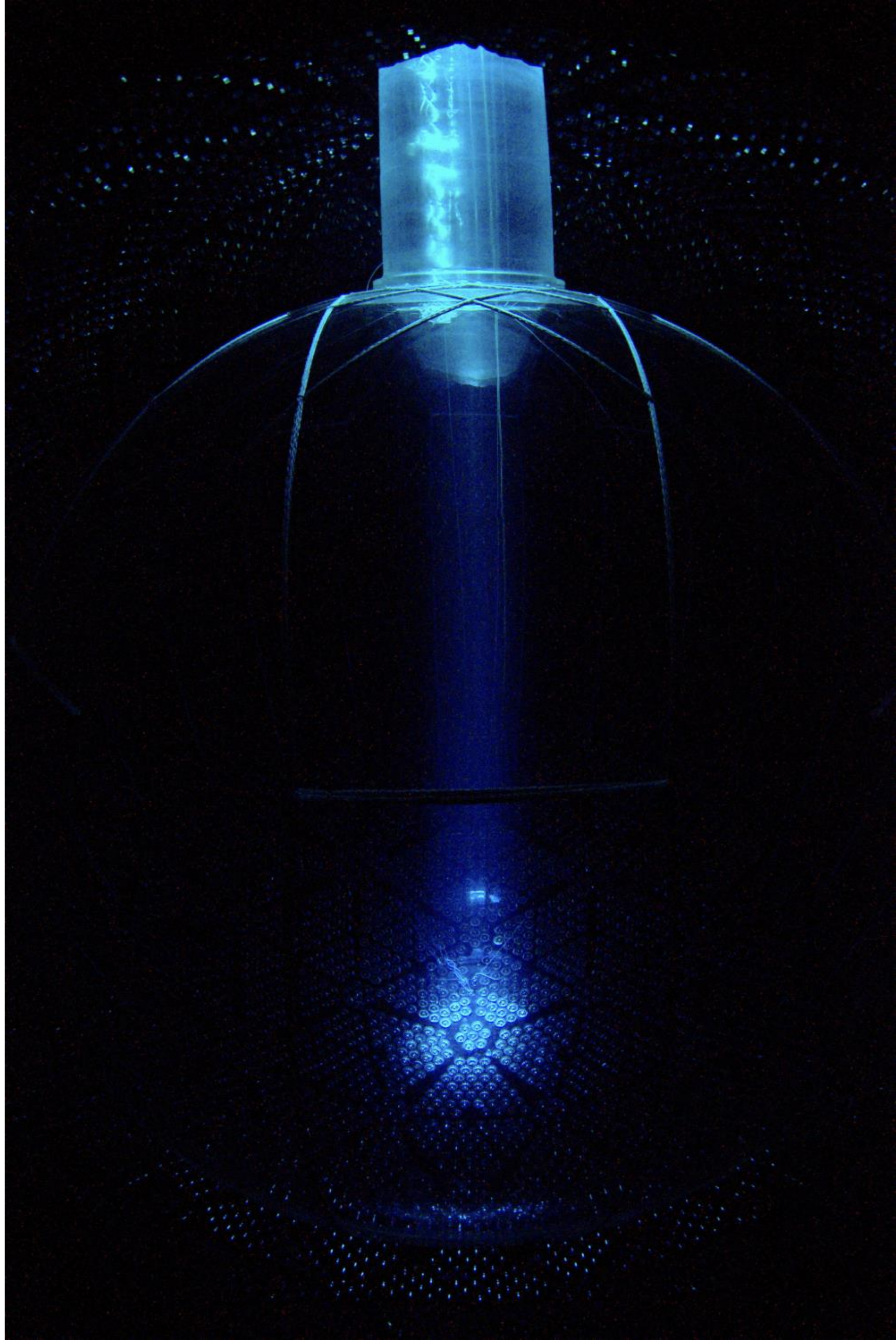
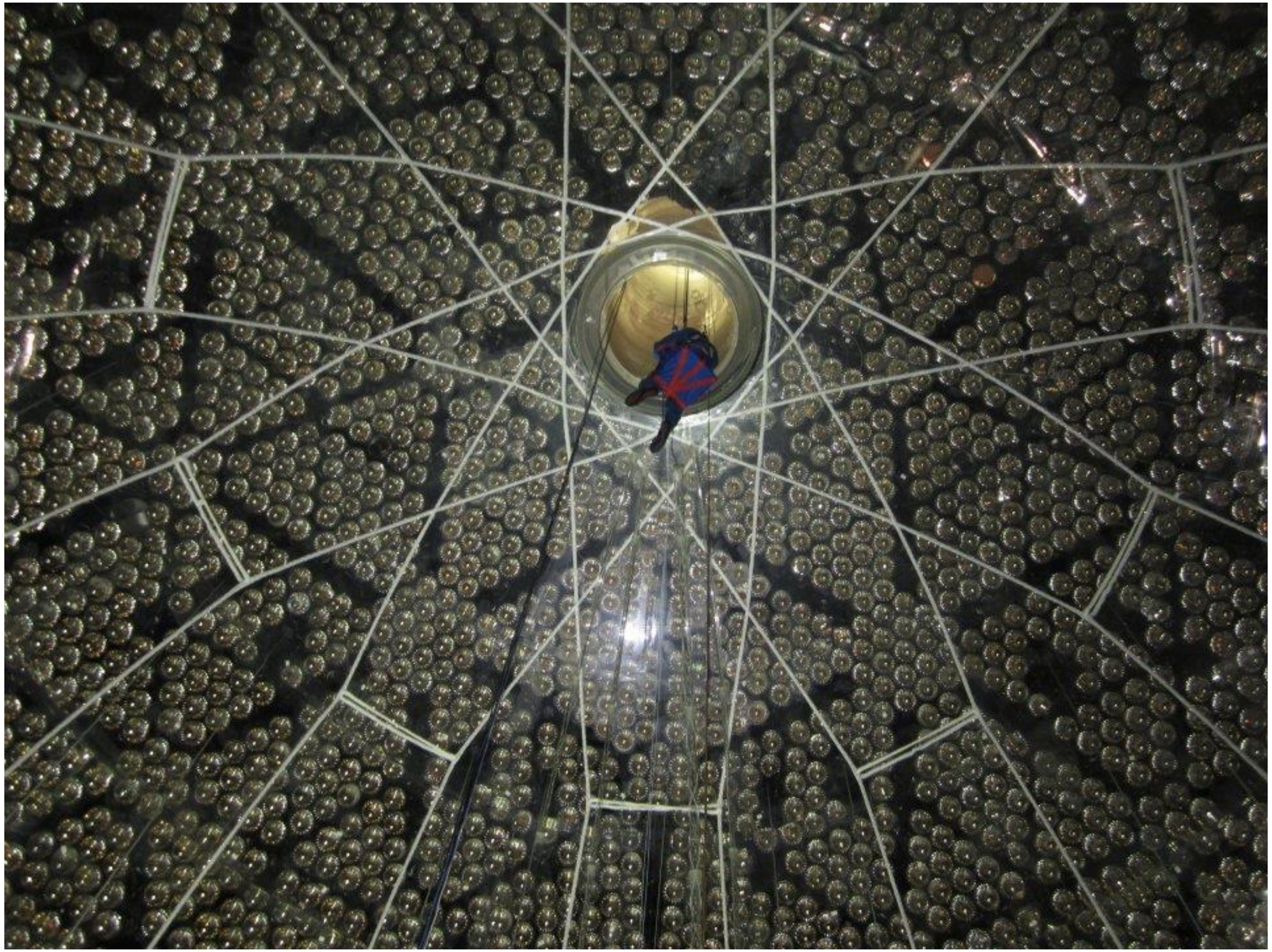
Recent Results

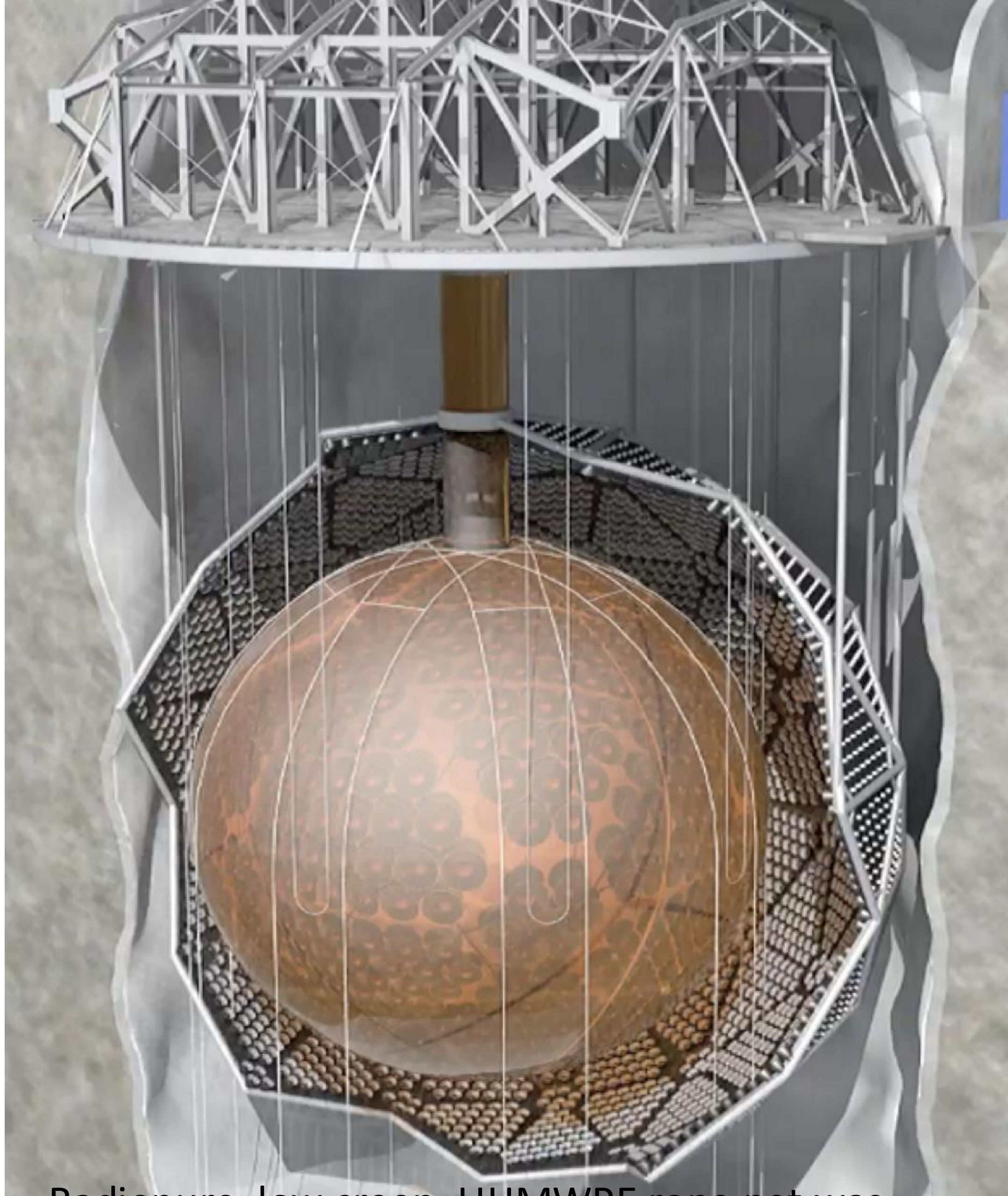
McDonald Institute 2024 Community Meeting

Mark Chen
Queen's University and CIFAR
August 8, 2024



SNO+ is the Sudbury Neutrino Observatory Filled with Liquid Scintillator





Radiopure, low creep, UHMWPE rope net was installed to hold down the 130-tonne buoyant force of the AV filled with liquid scintillator

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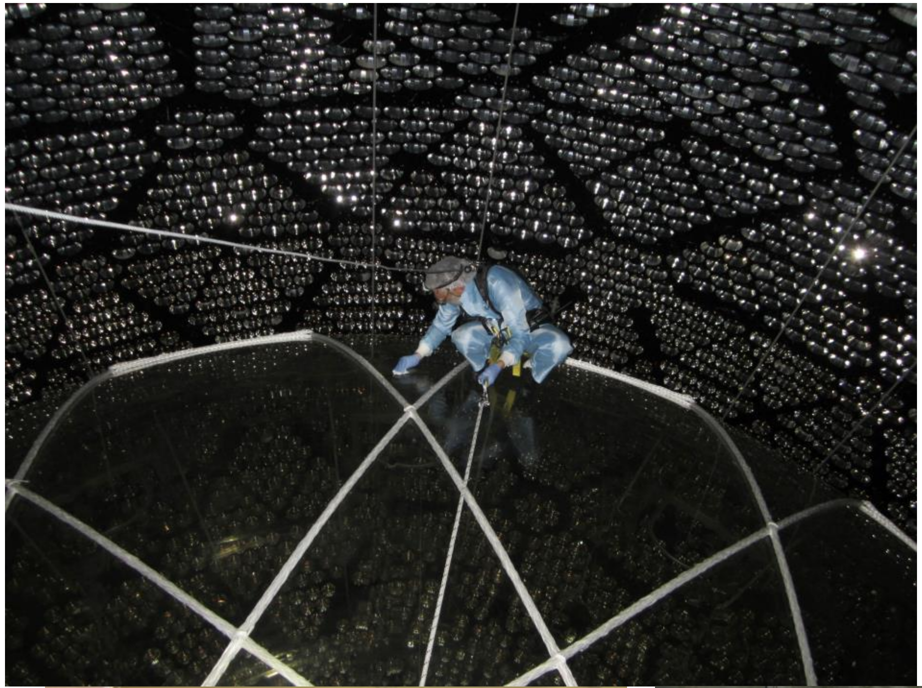

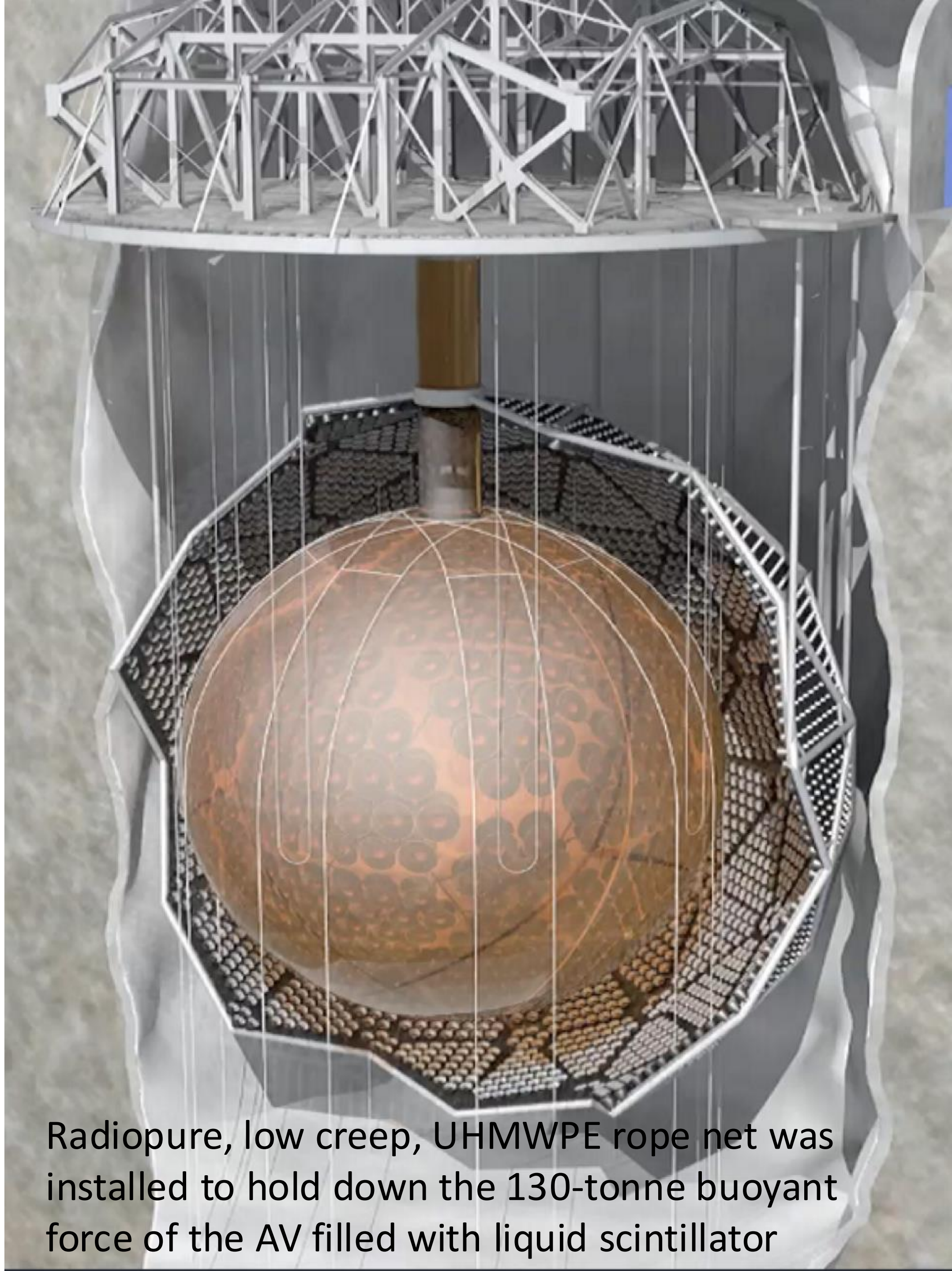

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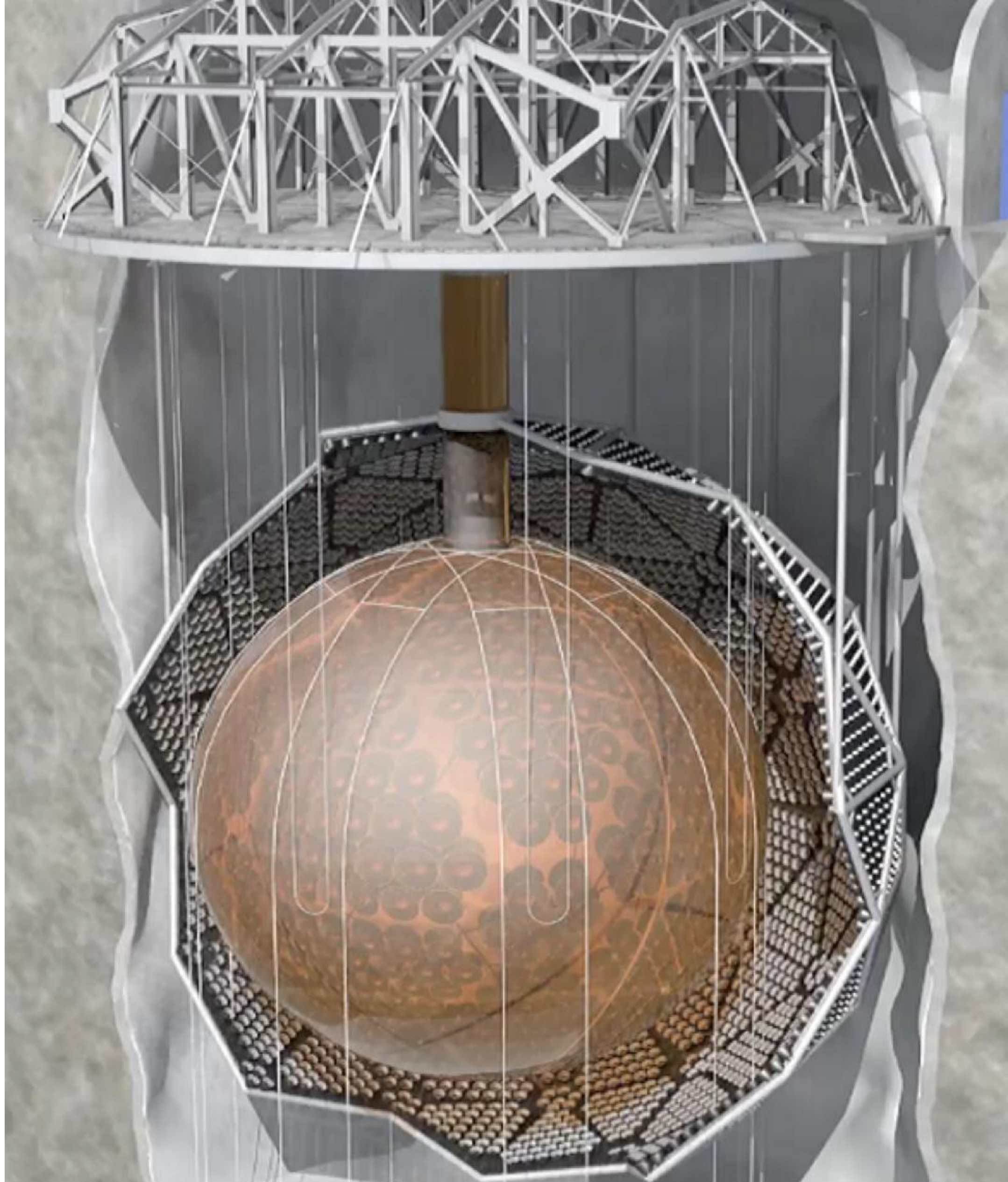

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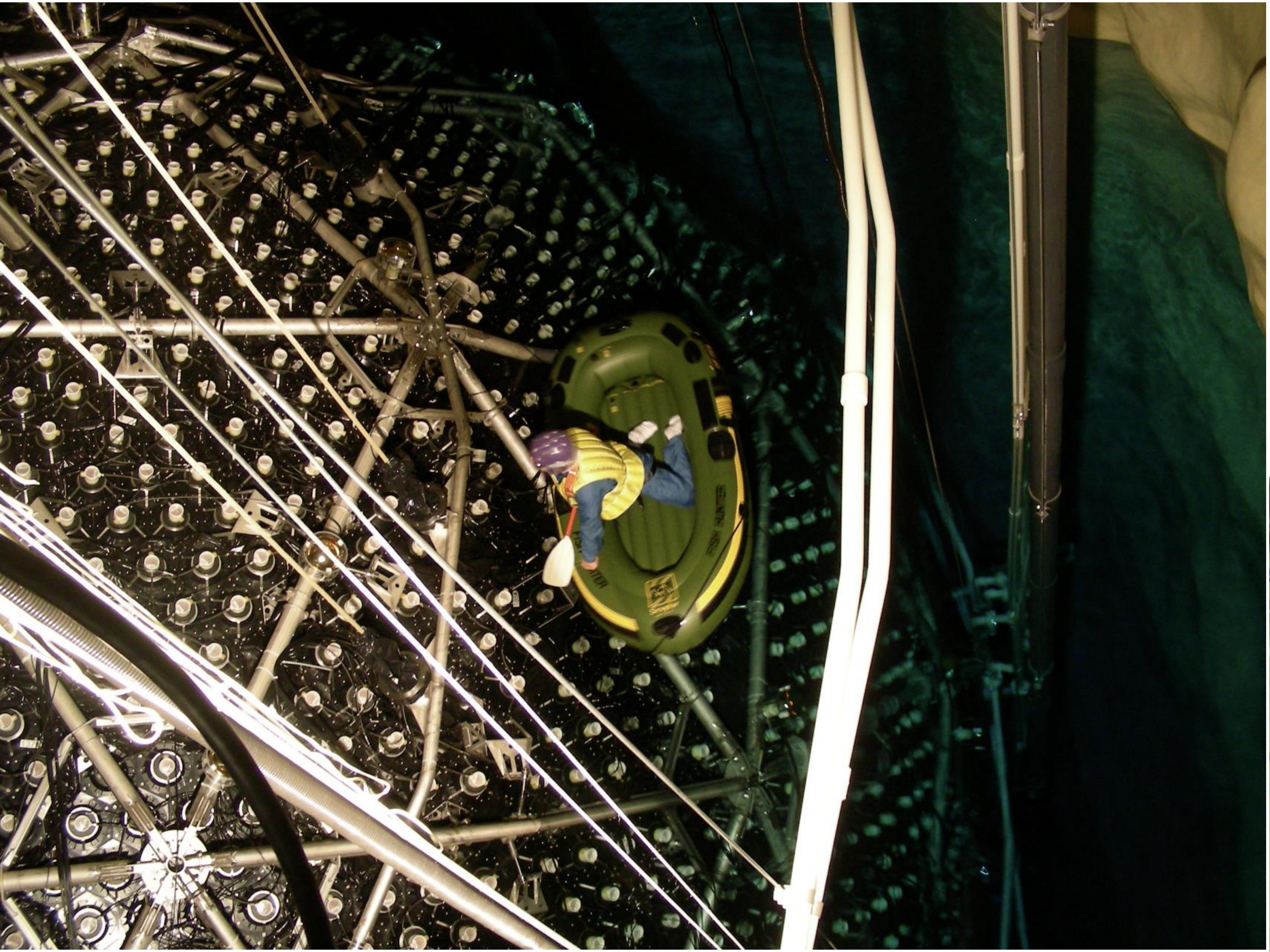



sevylor
HF 280
FISH HUNTER

SNO+ Data-taking Timeline

2017 2018 2019 2020 2021 2022 2023 2024 2025

Water phase

- High Rn
- Low Rn

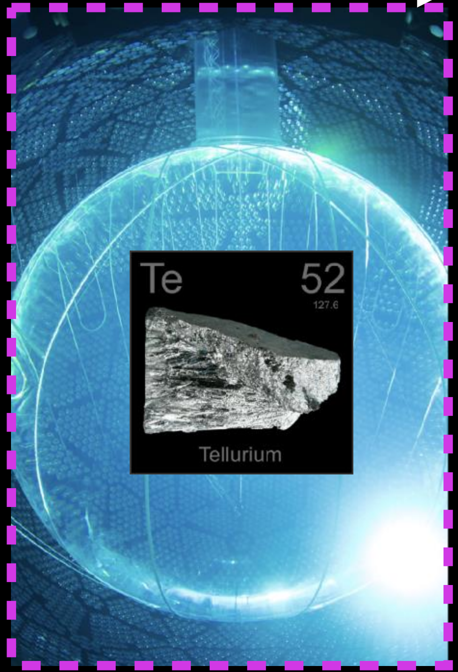
Partial-fill phase

Scintillator over water

Stop in fill due to Covid

Scintillator phase

- Low PPO
- Nominal PPO
- Added bis-MSB



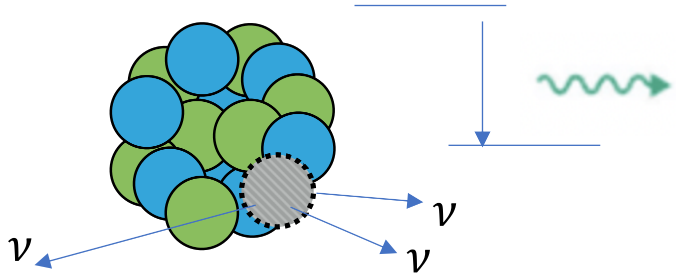
Next:

Tellurium-loaded phase

SNO+ Water Phase

Data taken
in 2017-2019

SNO+ Water Phase Physics Results



- World's best limits on invisible modes of nucleon decay
  - 2022 update, published in *Phys. Rev. D*

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]

Best limits are from SNO+

- Solar neutrinos
  - detected via neutrino-electron elastic scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

PHYSICAL REVIEW D **99**, 012012 (2019)

Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds

  - now with *even lower backgrounds*

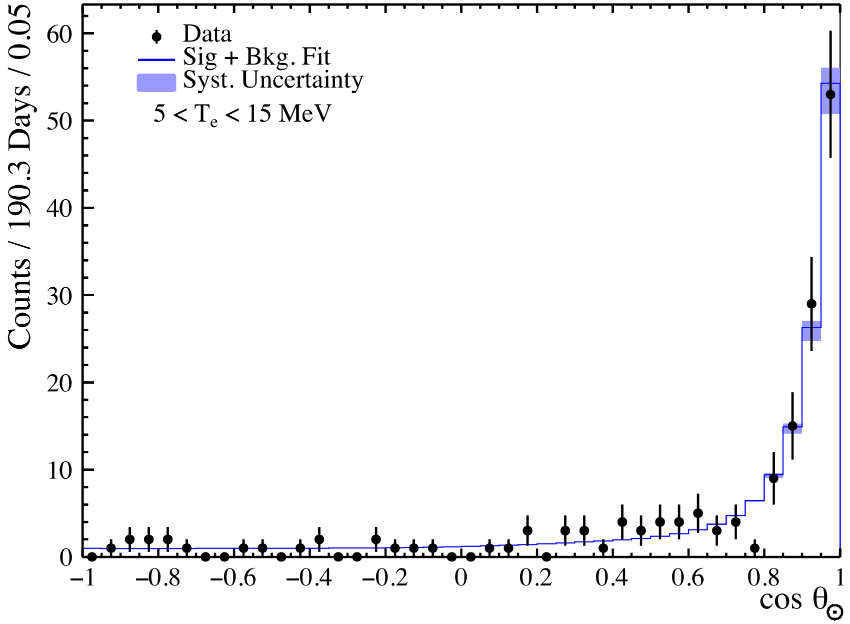
- First observation of reactor $\bar{\nu}_e + p \rightarrow e^+ + n$ events using *pure* water (undoped)
  - published in *Phys. Rev. Lett.*
  - made possible by ~50% neutron detection efficiency (highest in a water Cherenkov detector)

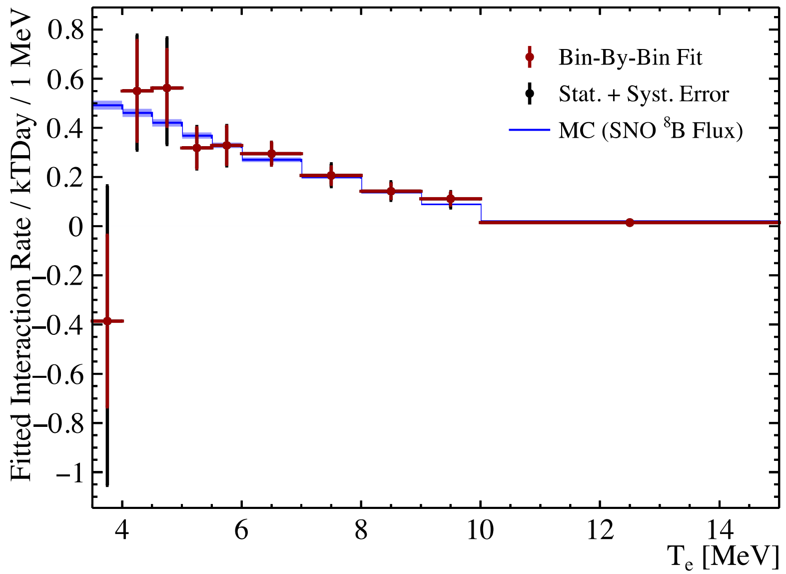
Recent Result

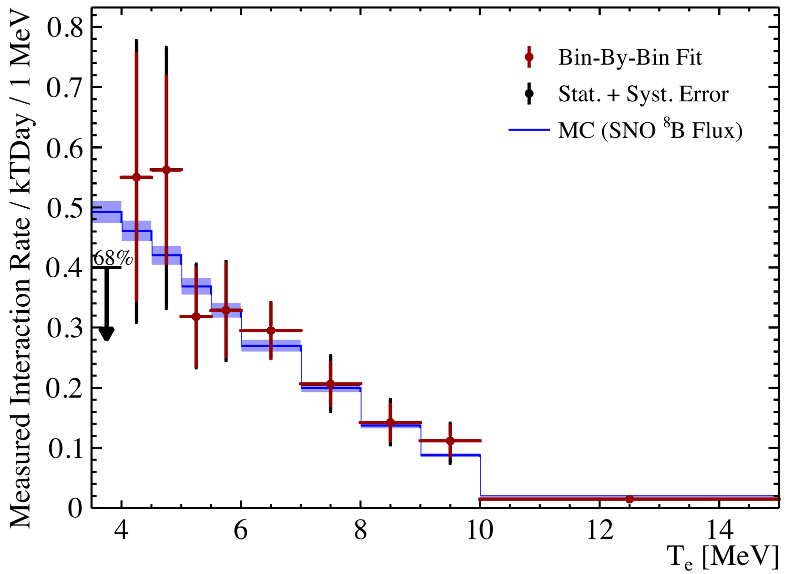
Submitted to PRD, arXiv:2407.17595

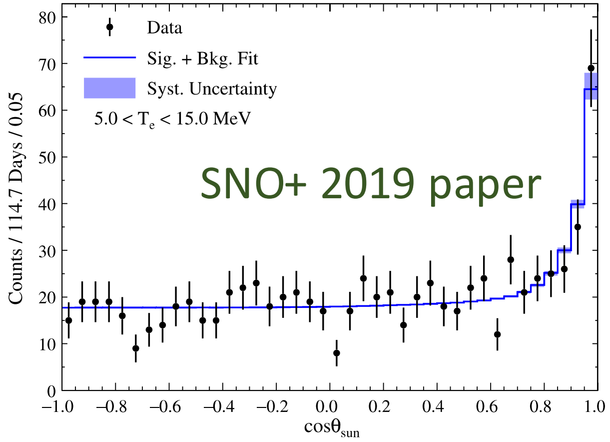
^{8}B solar neutrinos in SNO+ (Full Water Phase)

Measured flux: $5.36\ ^{+0.41}_{-0.39}(\text{stat.})\ ^{+0.17}_{-0.16}(\text{syst.}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$









SNO+ 2019 paper

same 5.0 MeV threshold

Recent result includes 190.3 live-days data from the extended water phase, with ~1/10 Rn levels

Recent Result

Submitted to PRD, arXiv:2407.17595

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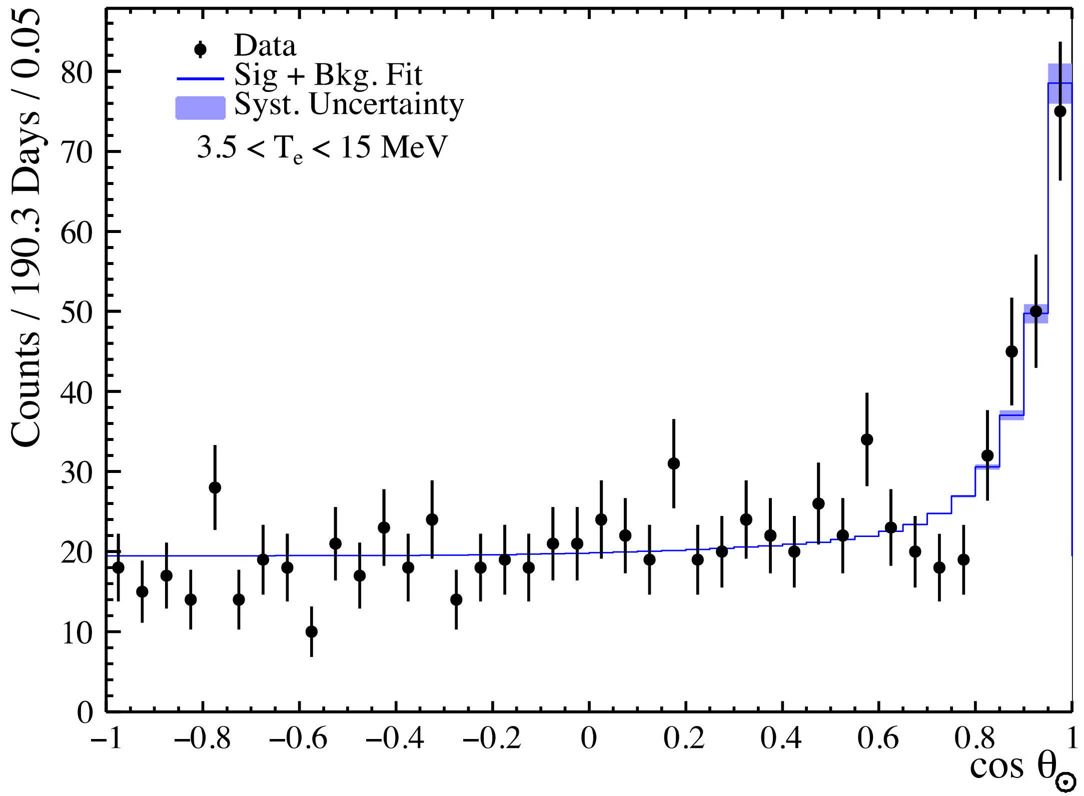


Even lower backgrounds!

Low energy threshold of 3.5 MeV (on par with the lowest achieved so far in a water Cherenkov detector)

Recent result includes 190.3 live-days data from the extended water phase, with ~1/10 Rn levels

SNO+ Water Phase

list of physics publications

- Set world-leading limits on invisible modes of nucleon decay, PRD **99**, 032008 (2019); PRD **105** 112012 (2022)
- "Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds", PRD **99**, 012012 (2019)
- Highest efficiency (~50%) for neutron detection in a water Cherenkov detector, PRC **102**, 014002 (2020)
- Detection of antineutrinos from distant reactors using only pure water, PRL **130**, 091801 (2023)

PHYSICAL REVIEW LETTERS **130**, 091801 (2023)

Editors' Suggestion | Featured in Physics

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

240 and 340 km away

- "Measurement of the ^{8}B solar neutrino flux using the full SNO+ Water Phase", arXiv:2407.17595 (2024)

technical papers

- SNO+ "Detector Paper" JINST **16**, P08059 (2021)
- SNO+ Scintillator Paper "Development, characterization and deployment of the SNO+ liquid scintillator" JINST **16**, P05009 (2021)
- Water Phase optical calibration JINST **16**, P10021 (2021)

SNO+ Scintillator Fill

Started in mid-late 2019 and was proceeding smoothly (post-commissioning) when the pandemic struck, halting all activities for >6 months. At 365 tonnes filled (~45%), SNO+ **partial-fill** benefited from a quiet period with no operations, allowing radon backgrounds to decay and background levels in the LS to be measured.

SNO+ Partial Fill

- LS backgrounds measured at

^{214}BiPo delayed coincidences for U chain

$(4.7 \pm 1.2) \times 10^{-17}\ g_U/g_{LAB}$

^{212}BiPo delayed coincidences for Th chain

$(5.3 \pm 1.5) \times 10^{-17}\ g_{Th}/g_{LAB}$

meeting SNO+ background targets for double beta decay

- Optical properties of LS 👍
- Also physics from SNO+ partial fill…

Event-by-Event Direction Reconstruction of Solar Neutrinos in SNO+ Liquid Scintillator

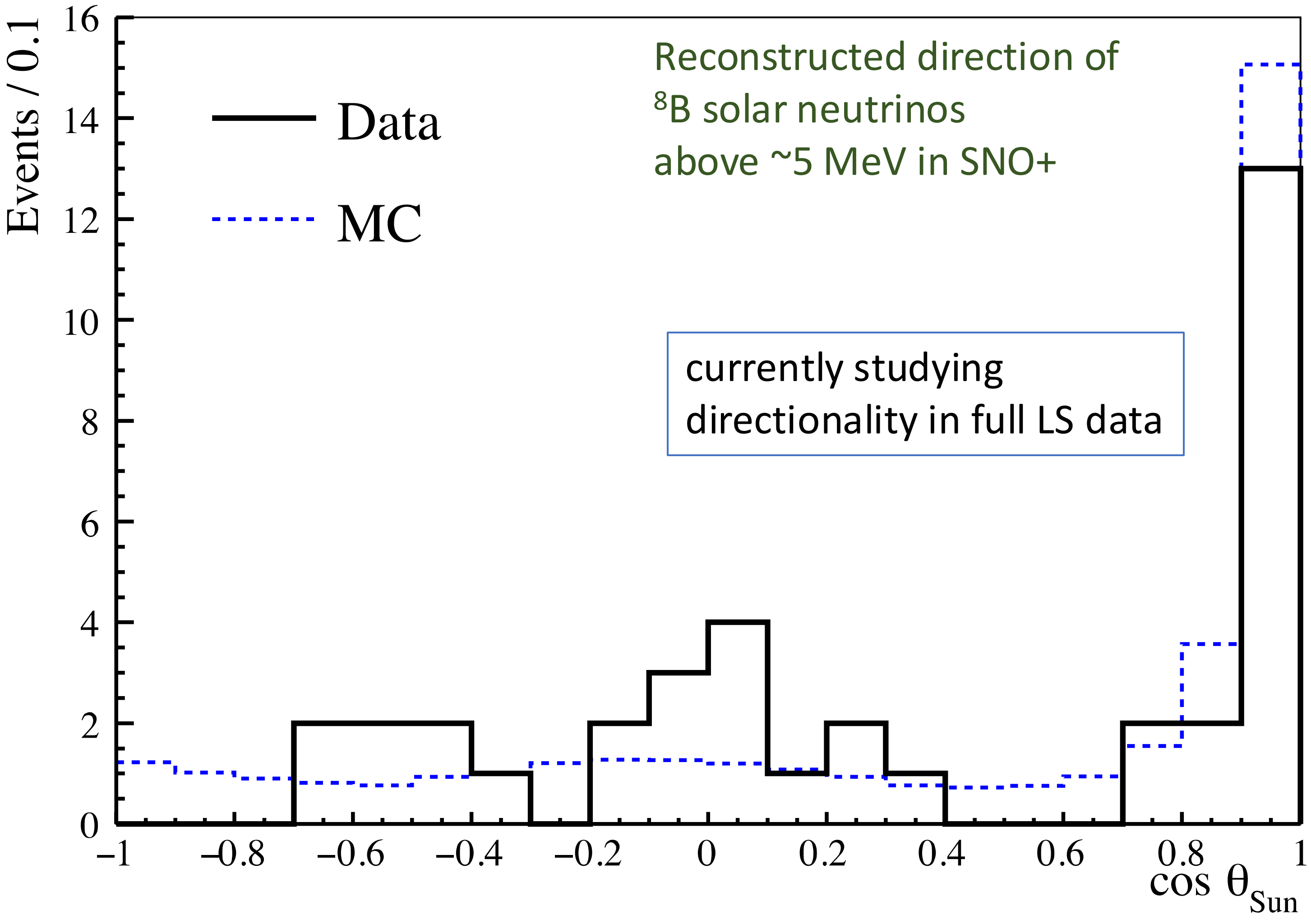
- Borexino had published the observation of a correlation between early PMT hits in the forward direction caused by the Cherenkov light produced by ^{7}Be and CNO solar neutrinos in liquid scintillator

  "Correlated and Integrated Directionality"

- SNO+ result: each recoil electron event's direction can be reconstructed by fitting with the combined Cherenkov+scintillation pdf

This is a first – event-by-event direction reconstruction of MeV events in liquid scintillator!

"Event-by-event direction reconstruction of solar neutrinos in a high light yield liquid scintillator", Phys. Rev. D **109**, 072002 (2024)



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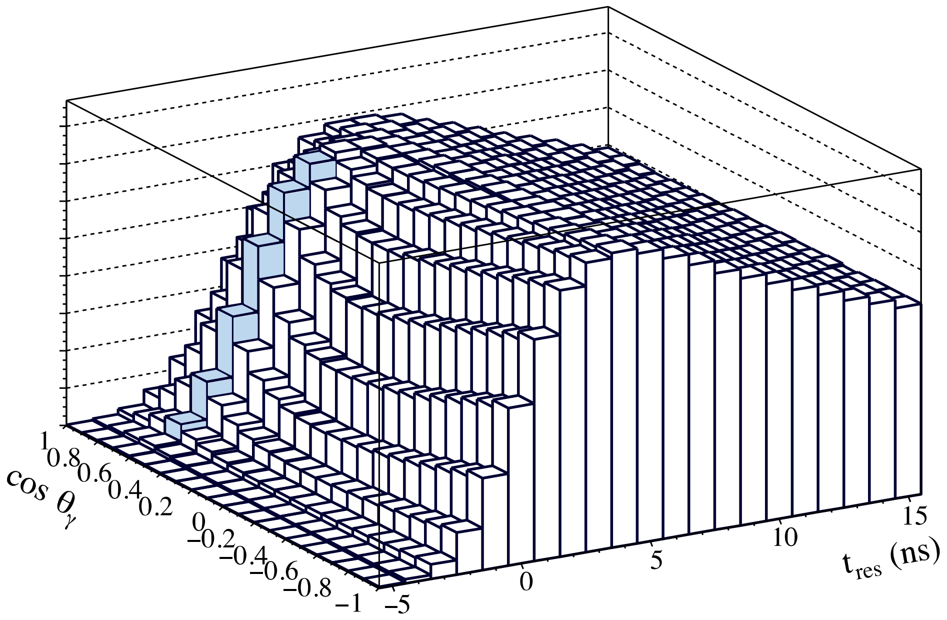

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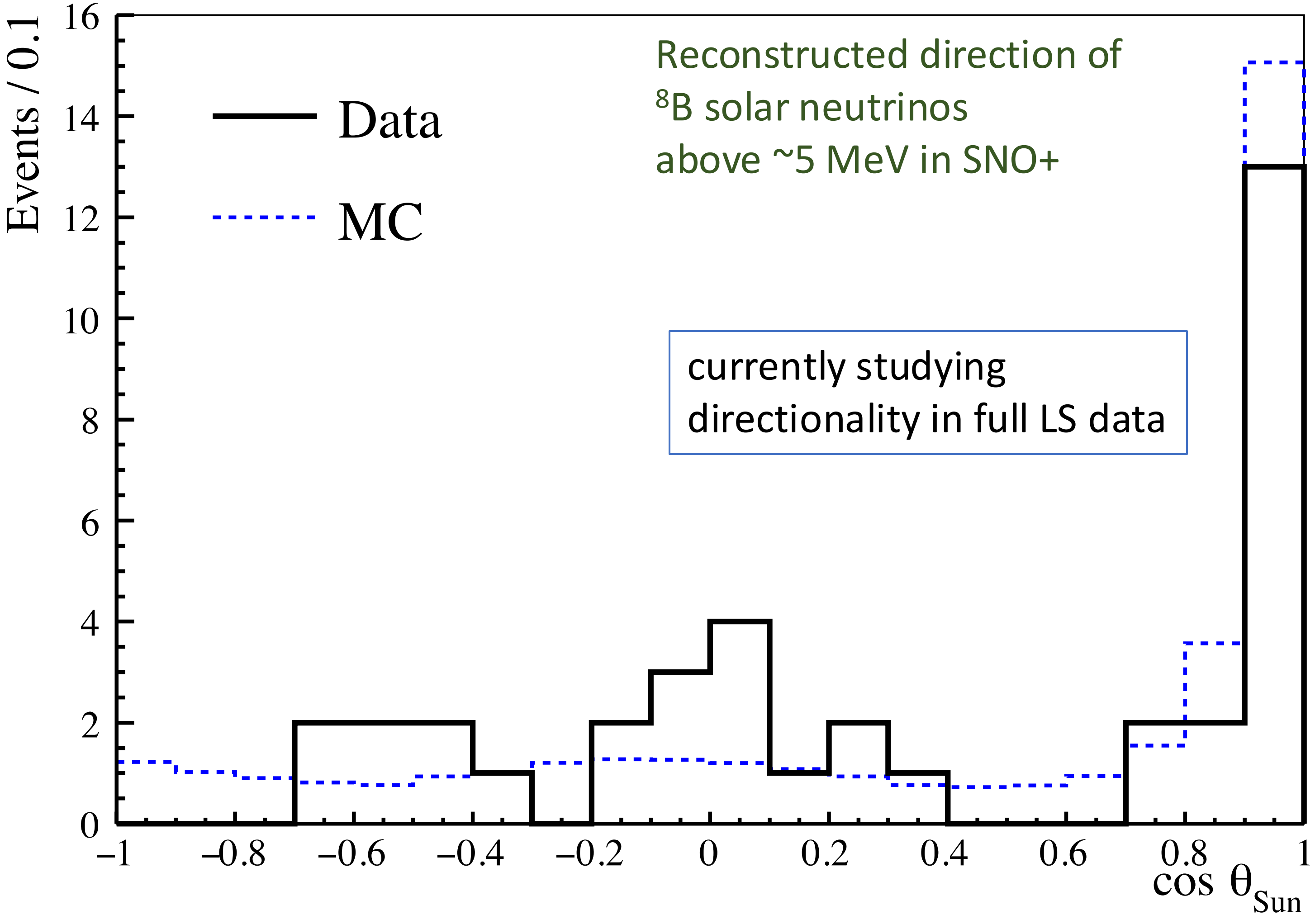


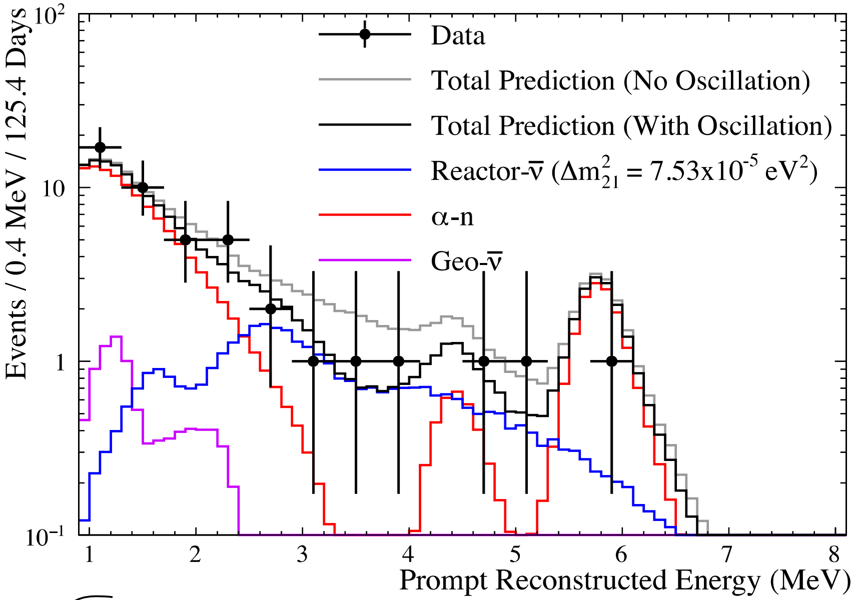
Recent Result

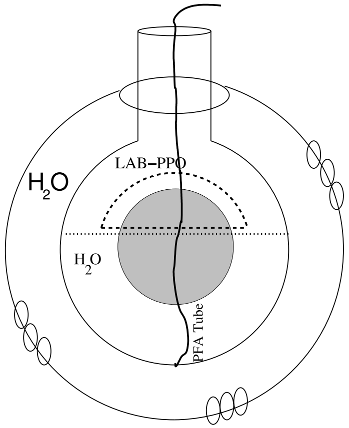
Submitted to PRD, arXiv:2405.19700

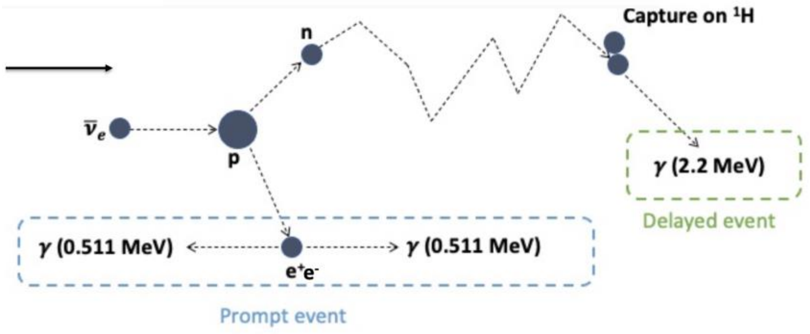
Antineutrino Physics with Partial-Fill Scintillator

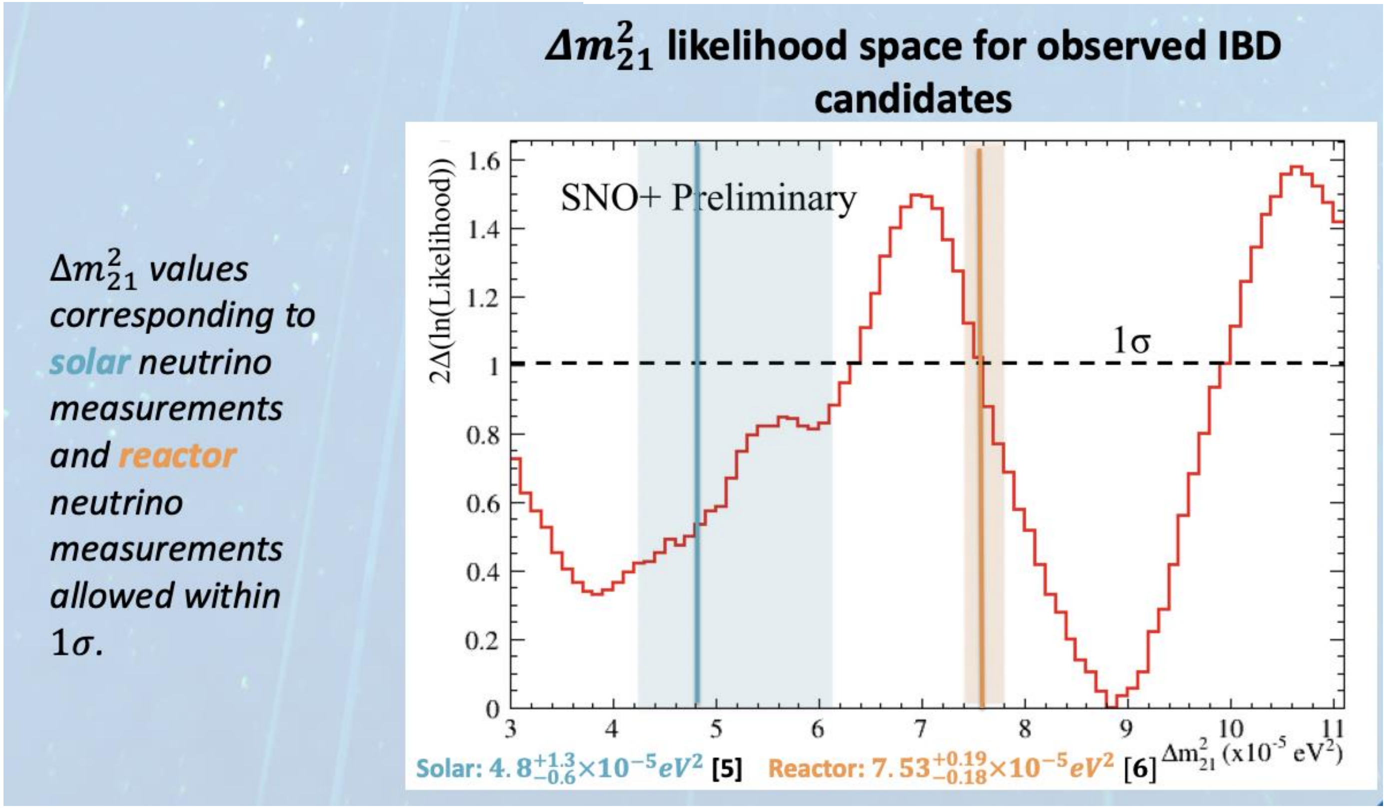
$\bar{\nu}_e + p \rightarrow e^+ + n$

Measured $\Delta m^2_{21} = 8.85^{+1.10}_{-1.33} \times 10^{-5}\ \mathrm{eV}^2$









SNO+ Scintillator Phase

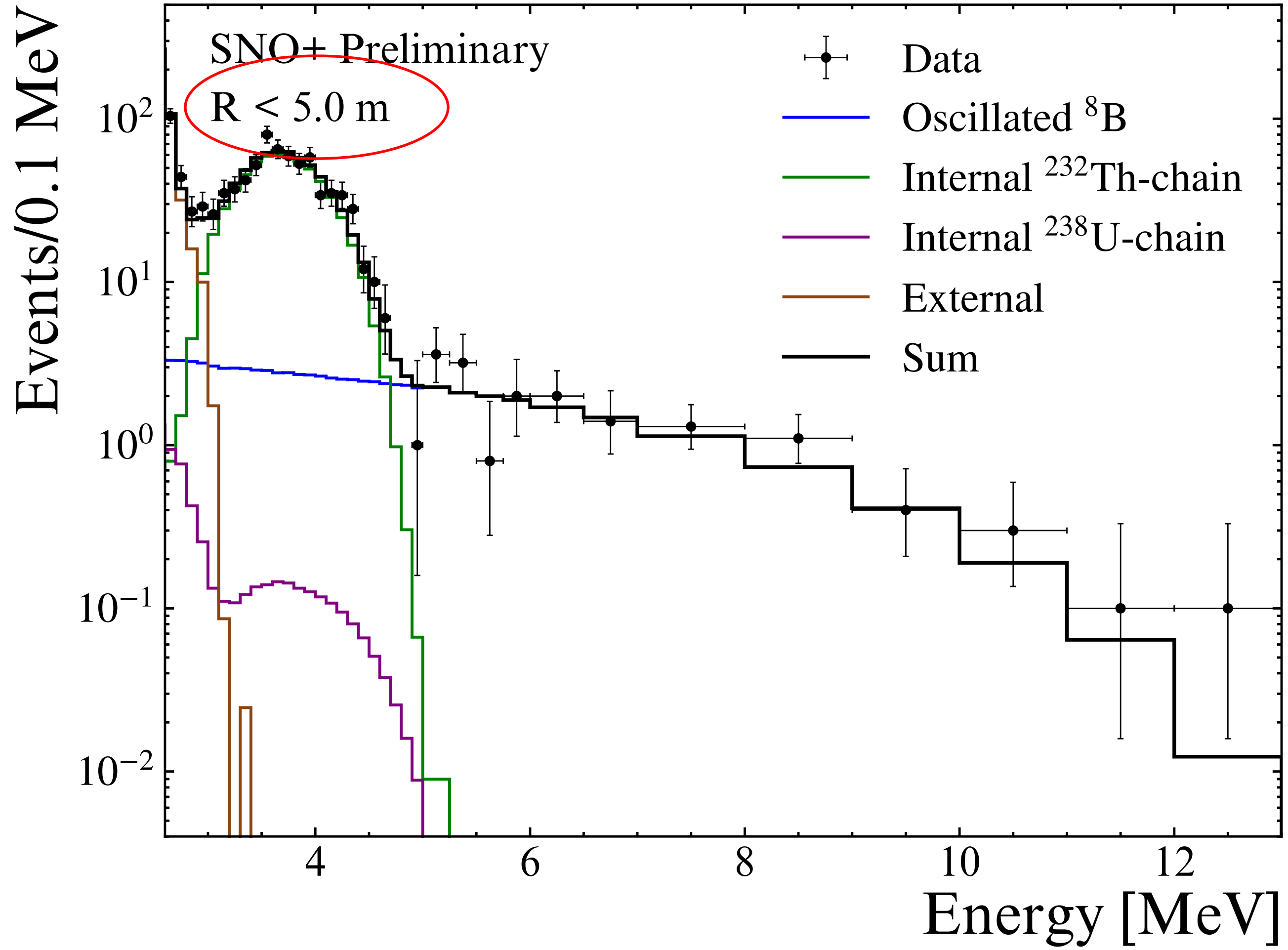
Physics Goals in the Scintillator Phase

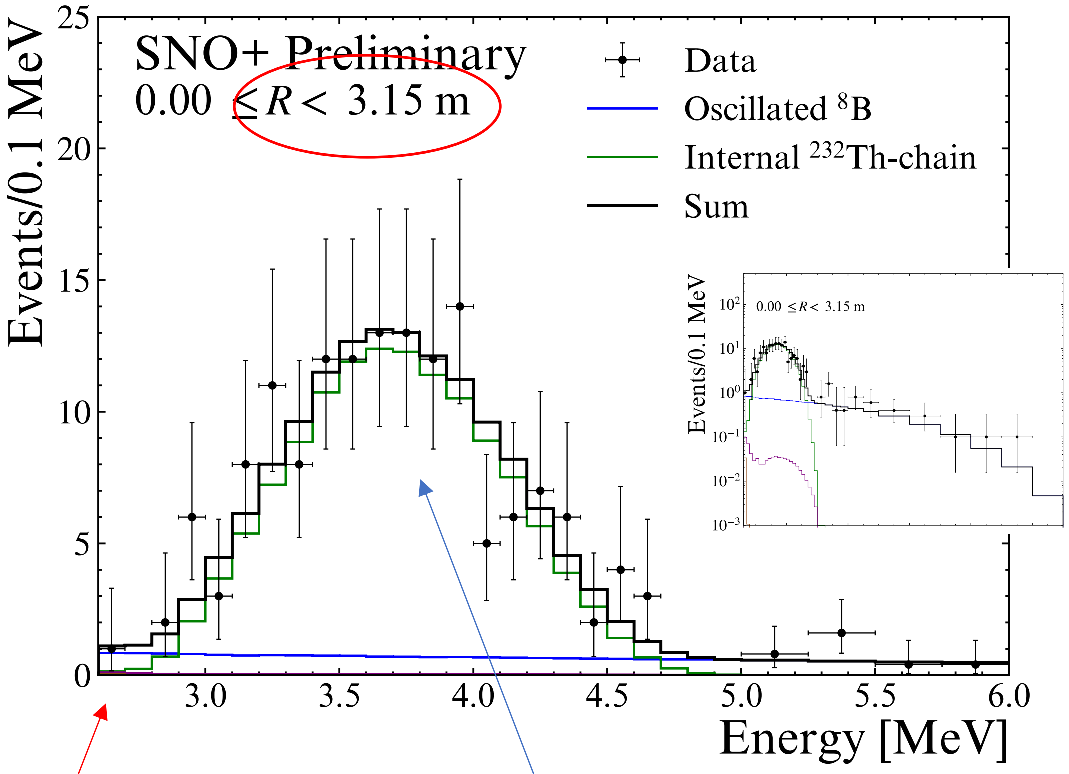
- Solar neutrinos (e.g. ^8B) at lower energies
- Reactor antineutrinos flux, spectrum, oscillations (Δm_{12}^2, in particular)
- Geo neutrinos
- SNO+ is supernova neutrino live
- and other “exotic” physics (e.g. MIMP dark matter searches, fermionic dark matter, DSNB – diffuse supernova neutrino background, nucleon decay)

Recent Result

SNO+ Scintillator Phase: ^{8}B Solar Neutrinos

Preliminary data as shown at Neutrino 2024





These energies for ^{8}B solar ν's haven't been studied before!

Internal Th backgrounds between 3 and 4 MeV – background rejection using directionality/multi-site being studied

Recent Result

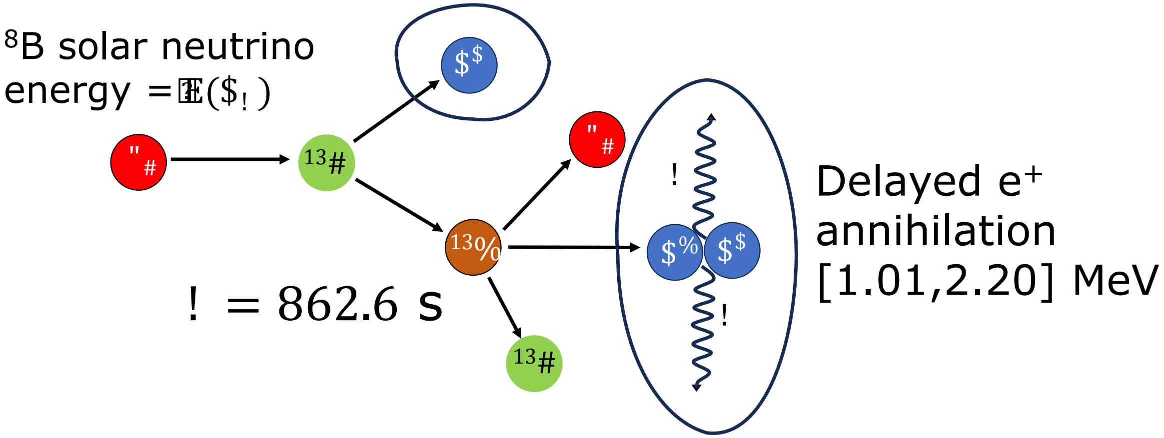
$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

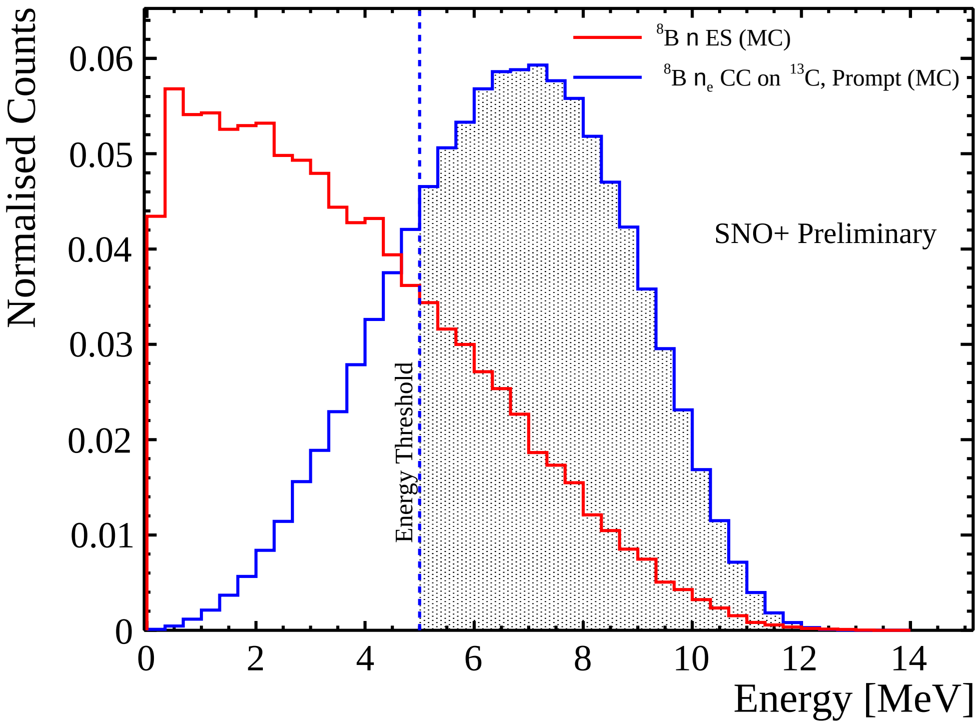
${}^{13}N \rightarrow e^+ + {}^{13}C + \nu_e$

Charged-current ν_e capture on ^{13}C

Up-to-now unobserved CC reaction for electron neutrinos (solar ν_e)

Prompt e$^-$ energy $= \mathrm{E}(\boldsymbol{\nu}_!) - 2.2\ MeV$





^{13}C only 1.1% isotopic abundance; but ~12× higher cross section per target than ^{8}B solar neutrino ES on electrons

Cosmogenic backgrounds (e.g. ^{11}Be) obscured this reaction in previous experiments but at SNOLAB depth, the main background is an accidental coincidence with a ^{8}B solar neutrino ES event

Recent Result

$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

${}^{13}N \rightarrow e^+ + {}^{13}C + \nu_e$

Charged-current ν_e capture on ^{13}C

150.51 live-days in SNO+ analyzed

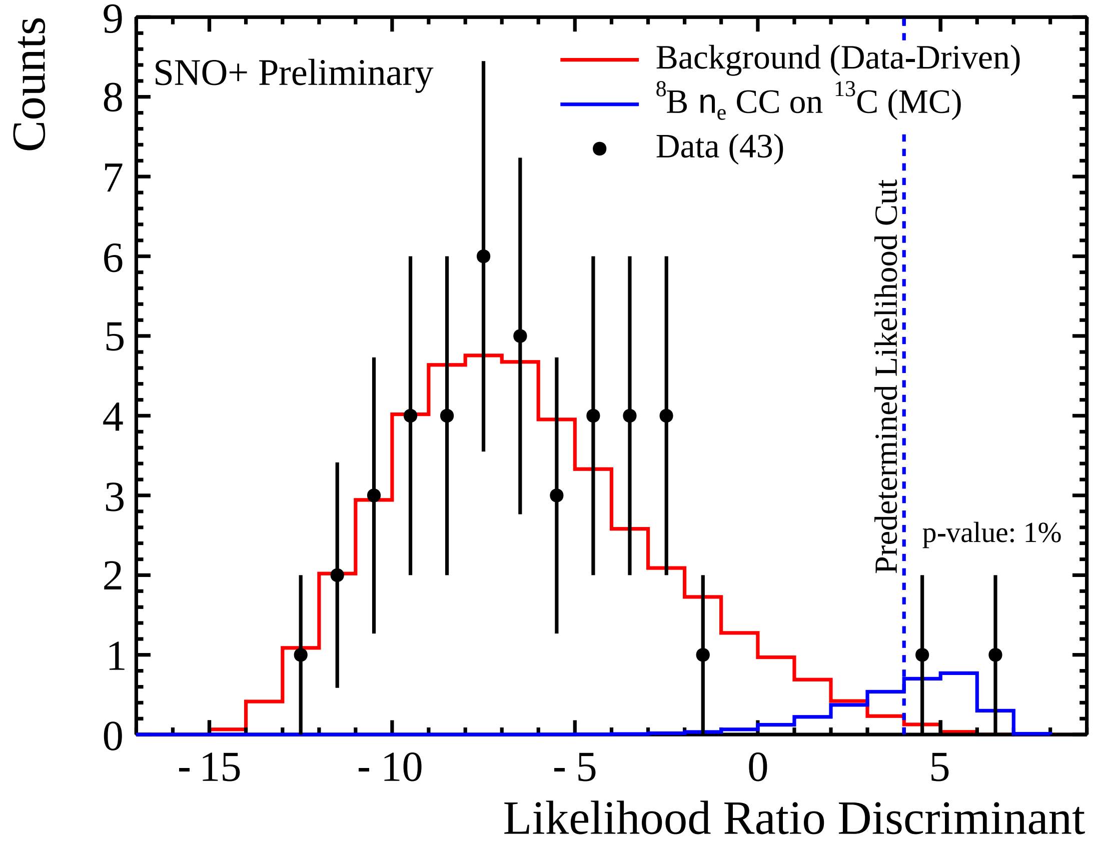
2 events found!

(0.1-0.3 backgrounds expected)

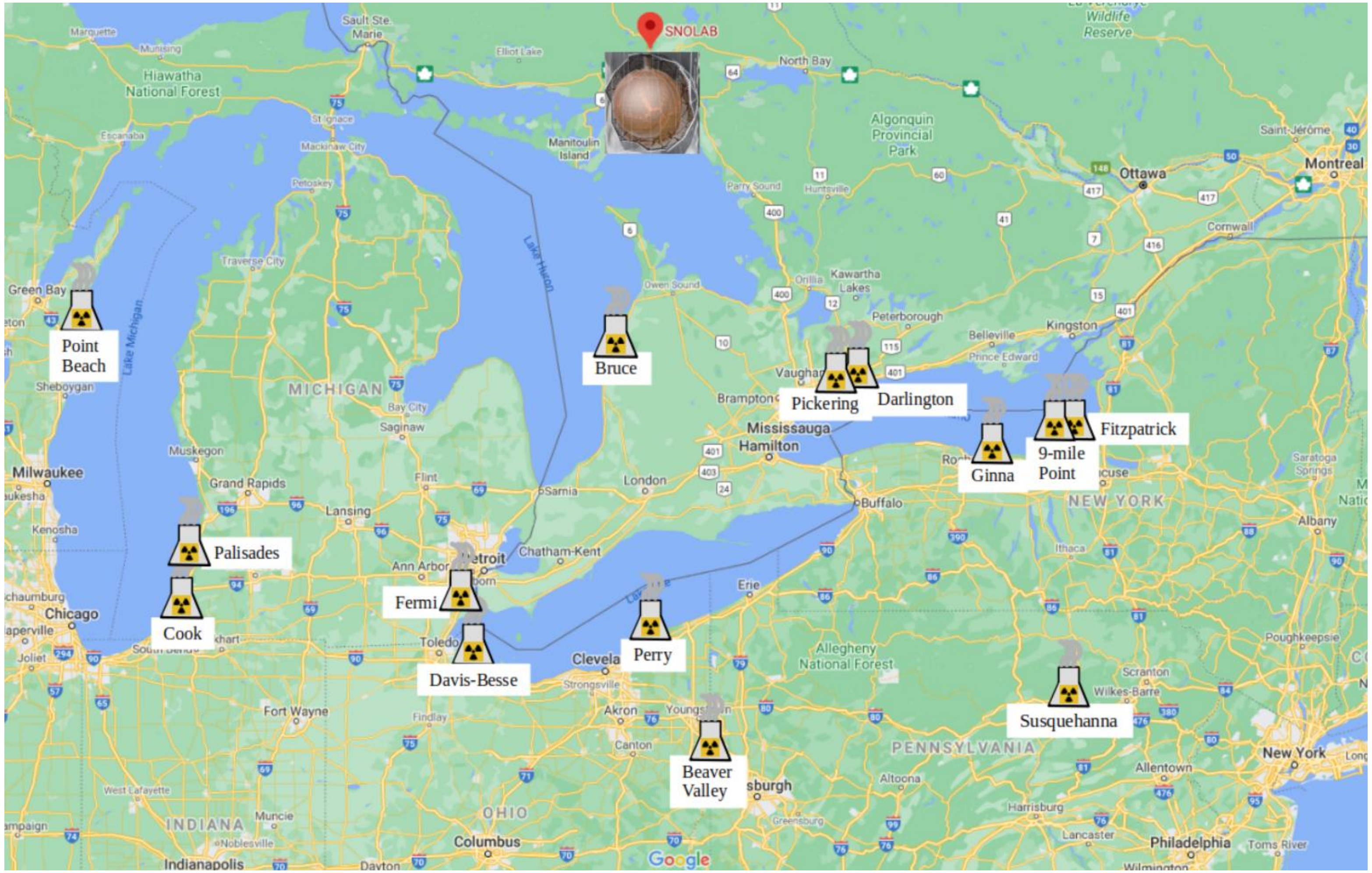
Indication of a signal!

Accumulating more statistics; publication in preparation…

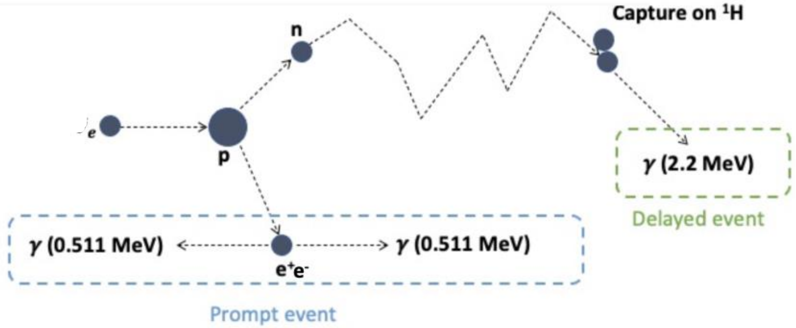
EXPECTED	BOX	LIKELIHOOD
BACKGROUND	0.31	0.17
SIGNAL	1.83	1.79



Reactor Antineutrinos in SNO+



Inverse Beta Decay (IBD)



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

<u>Coincidence event</u>

Prompt – positron kinetic energy (several MeV)

plus 1.022 MeV from annihilation γ's

Delayed – neutron capture 2.2 MeV γ

Recent Result

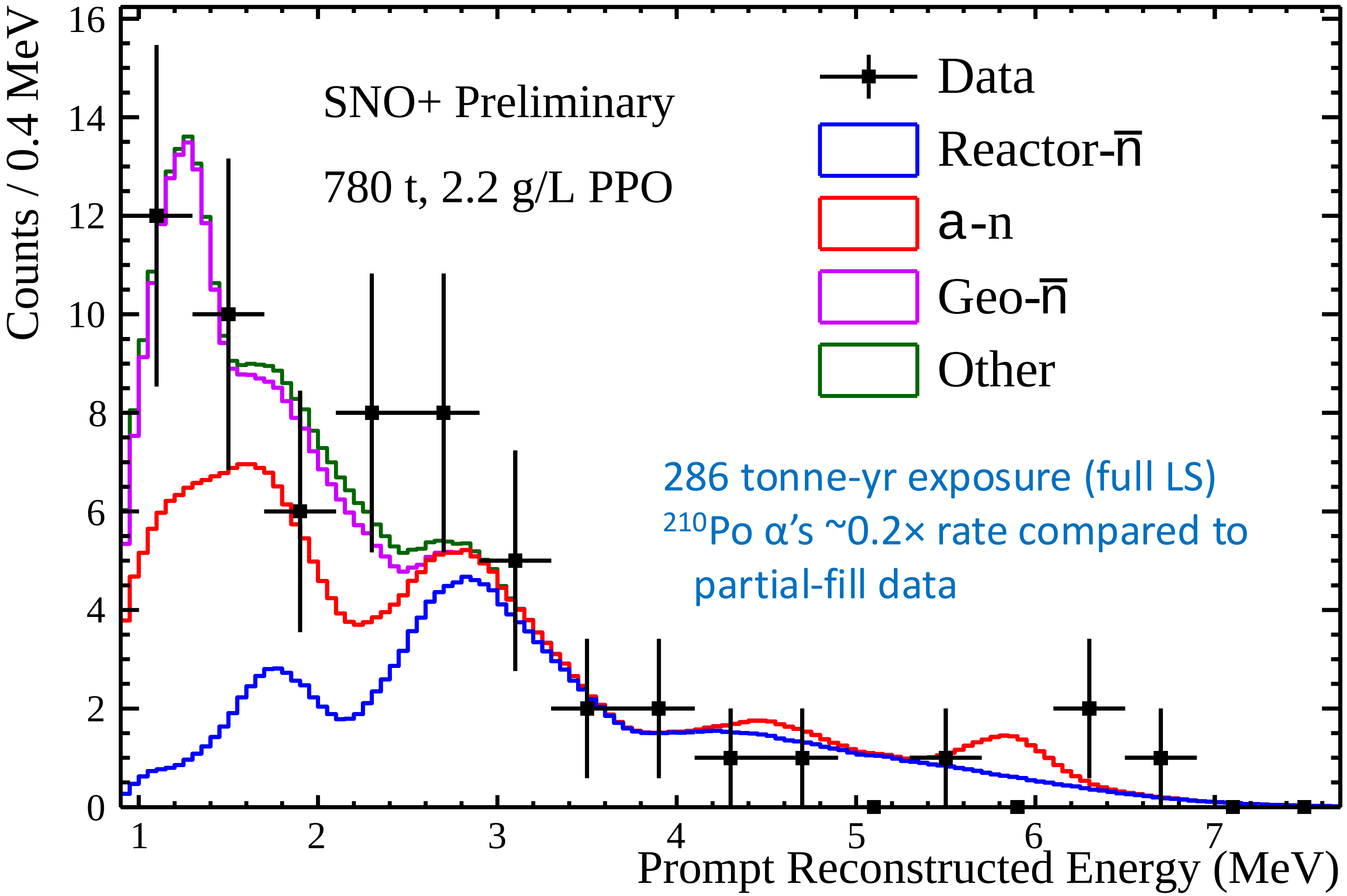
SNO+ Scintillator Phase: Antineutrinos in Full LS

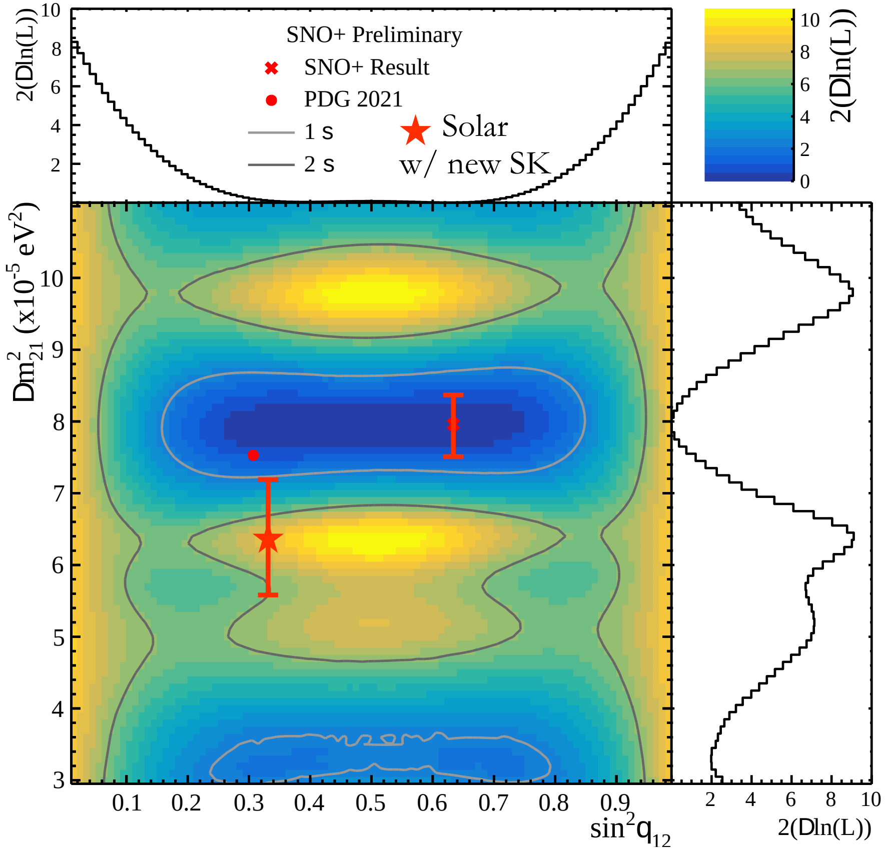
Preliminary data as shown at Neutrino 2024

SNO+ is detecting geo neutrinos!!

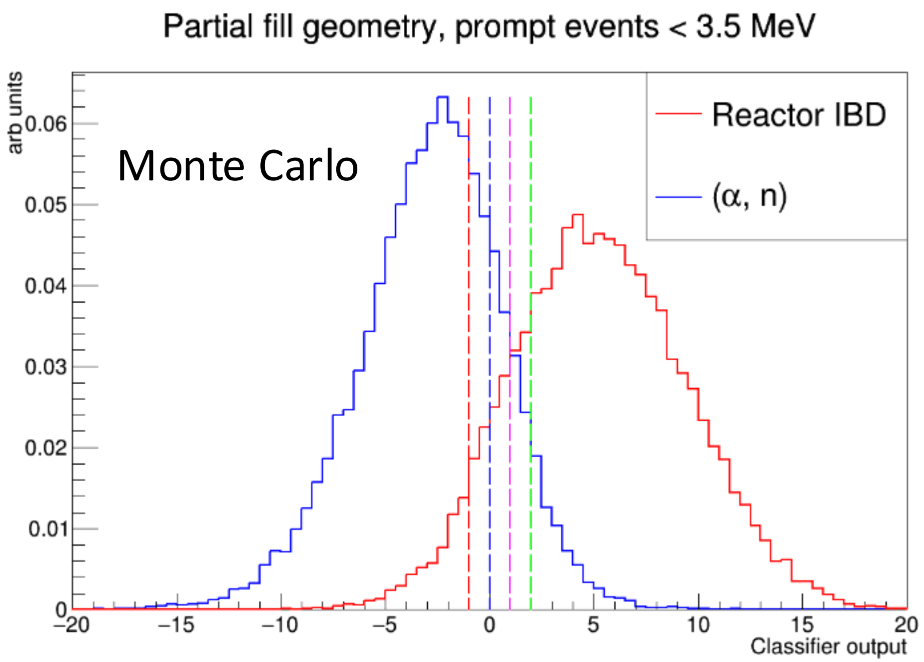
Ultra-prelim geo neutrino flux: 64 ± 44 TNU

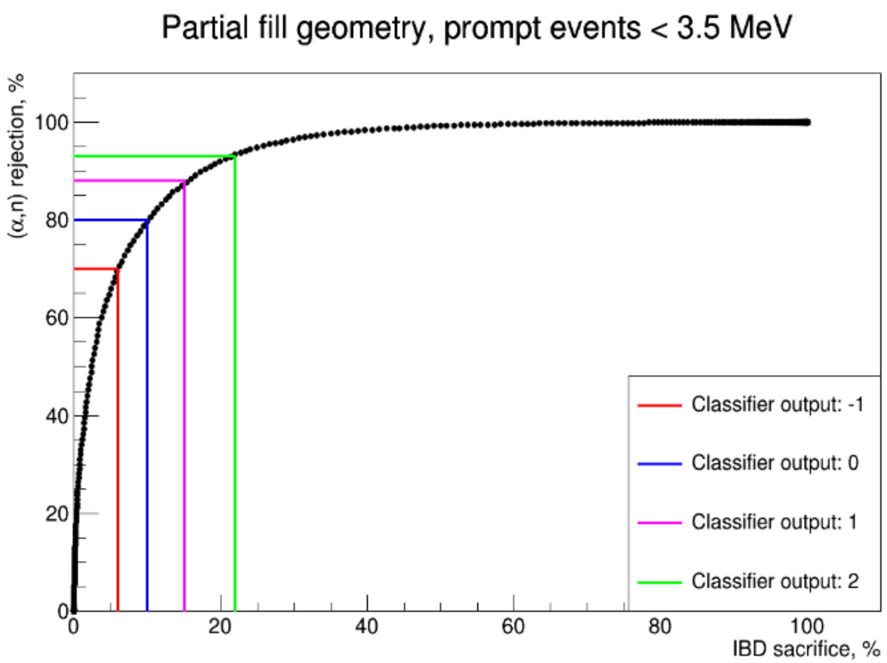
Measured $\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5}$ eV²

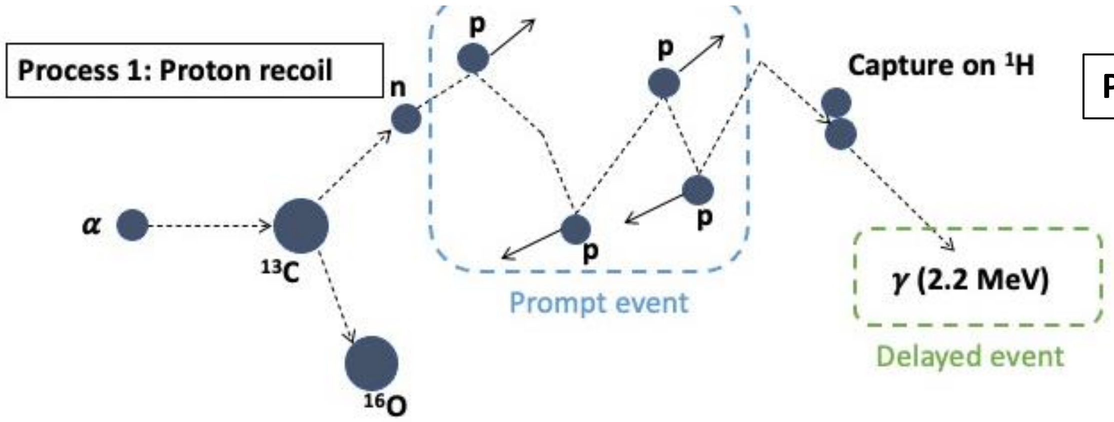


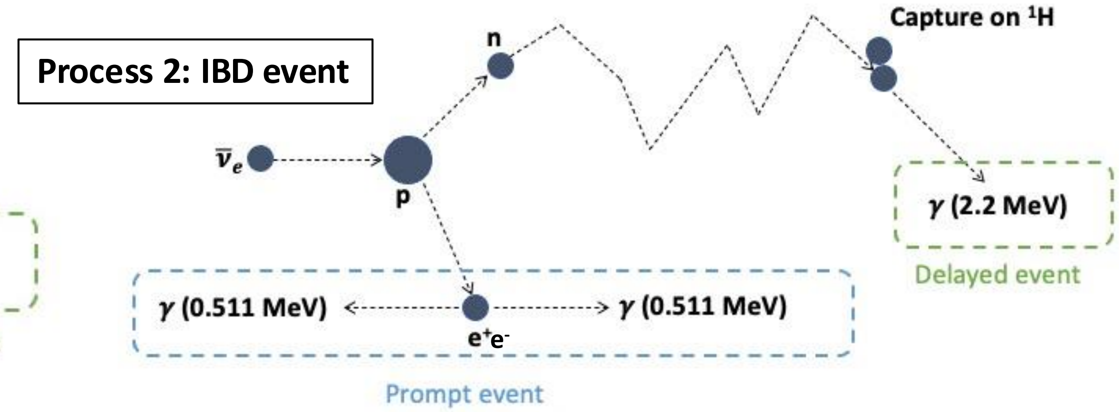


(α,n) Classifier (tested in partial-fill) – New SNO+ analysis technique

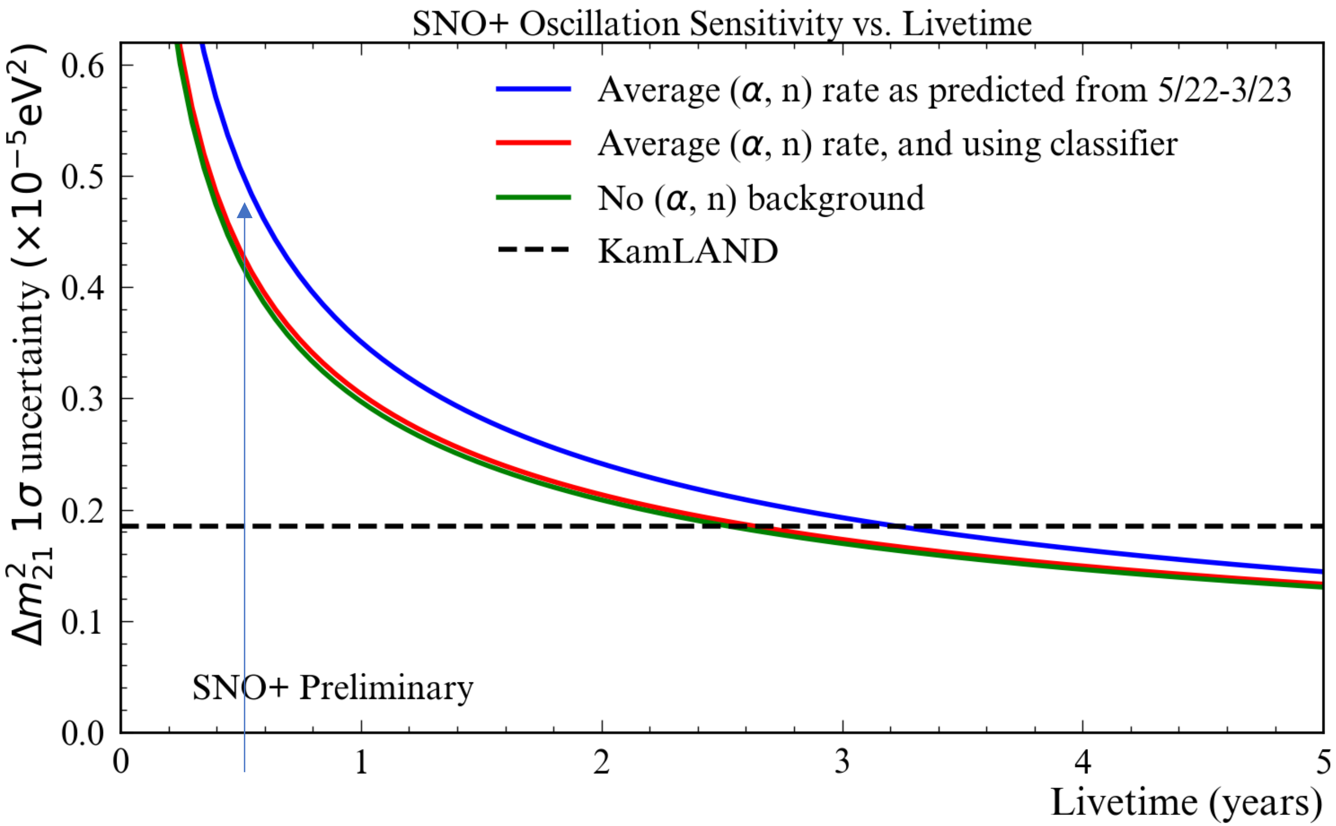


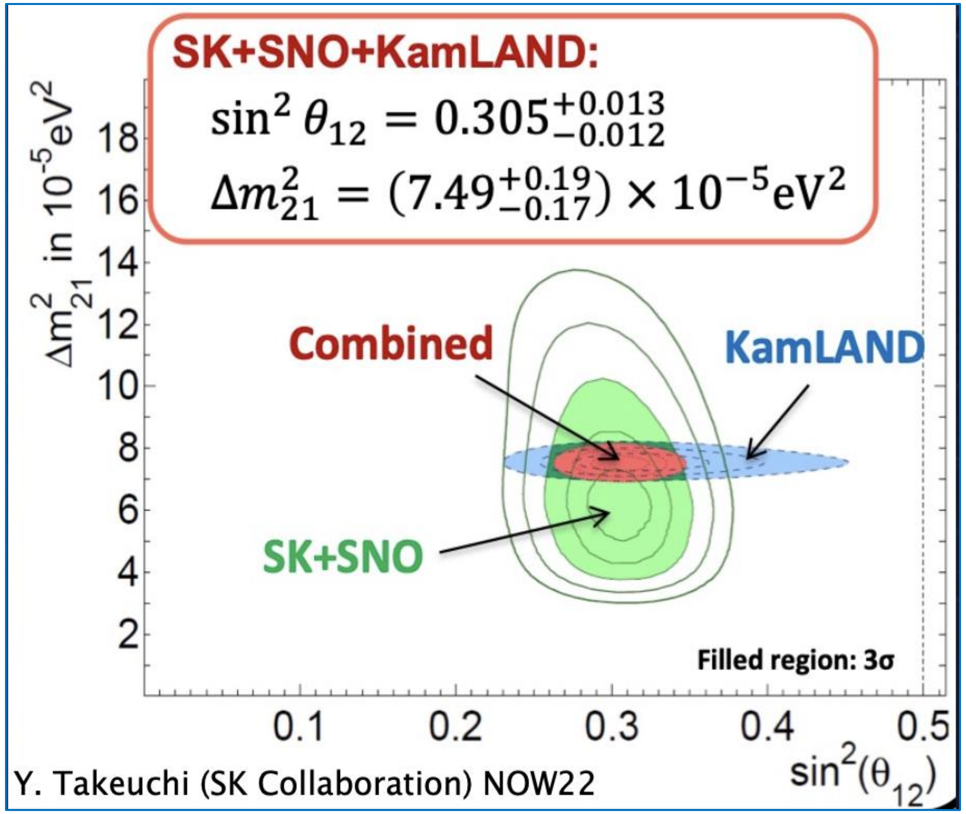






Objectives for SNO+ Scintillator Phase Antineutrino: Reactor Antineutrinos Δm^2_{12}

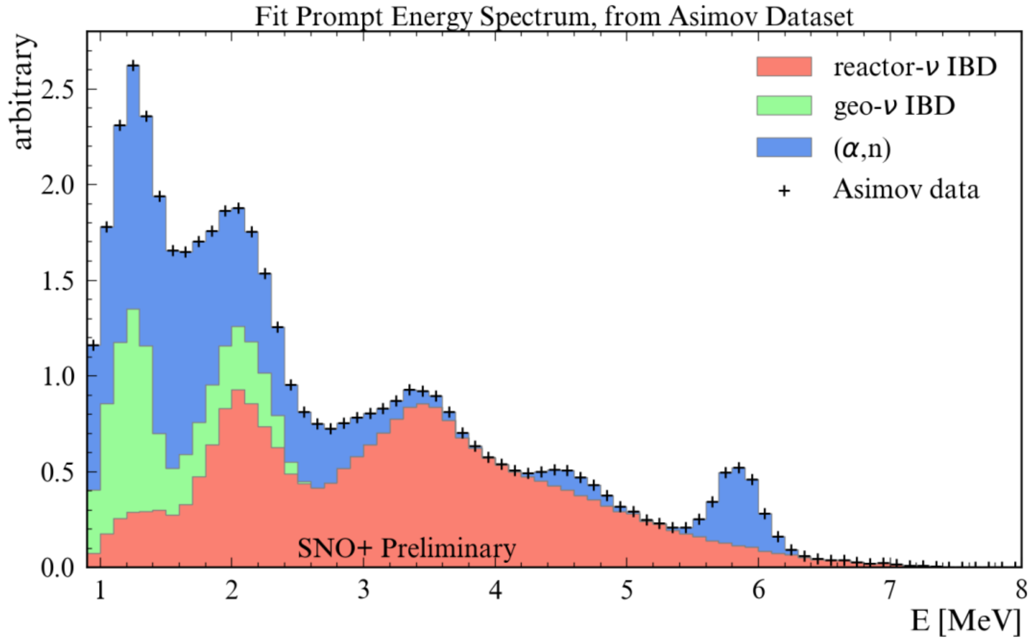


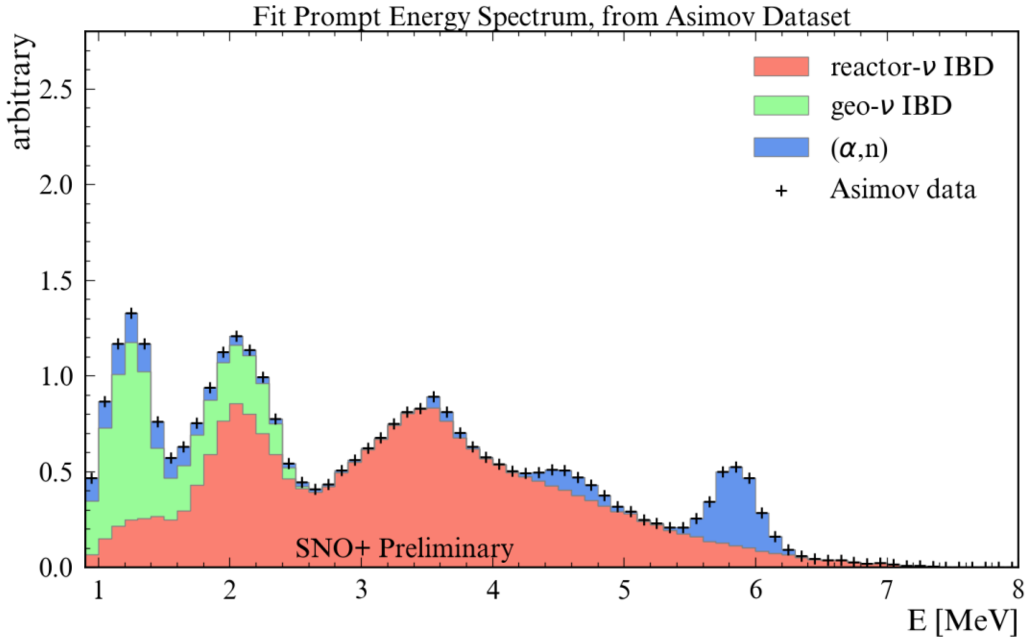


test Δm^2_{12} with ν_e (solar) and $\bar{\nu}_e$ (reactor)
can easily distinguish 5.0 from 7.5 ($\times 10^{-5}$ eV^2)

Objectives for SNO+ Scintillator Phase Antineutrino:
Geo Neutrinos

Simulated impact on prompt energy spectrum from (α,n) classifier:



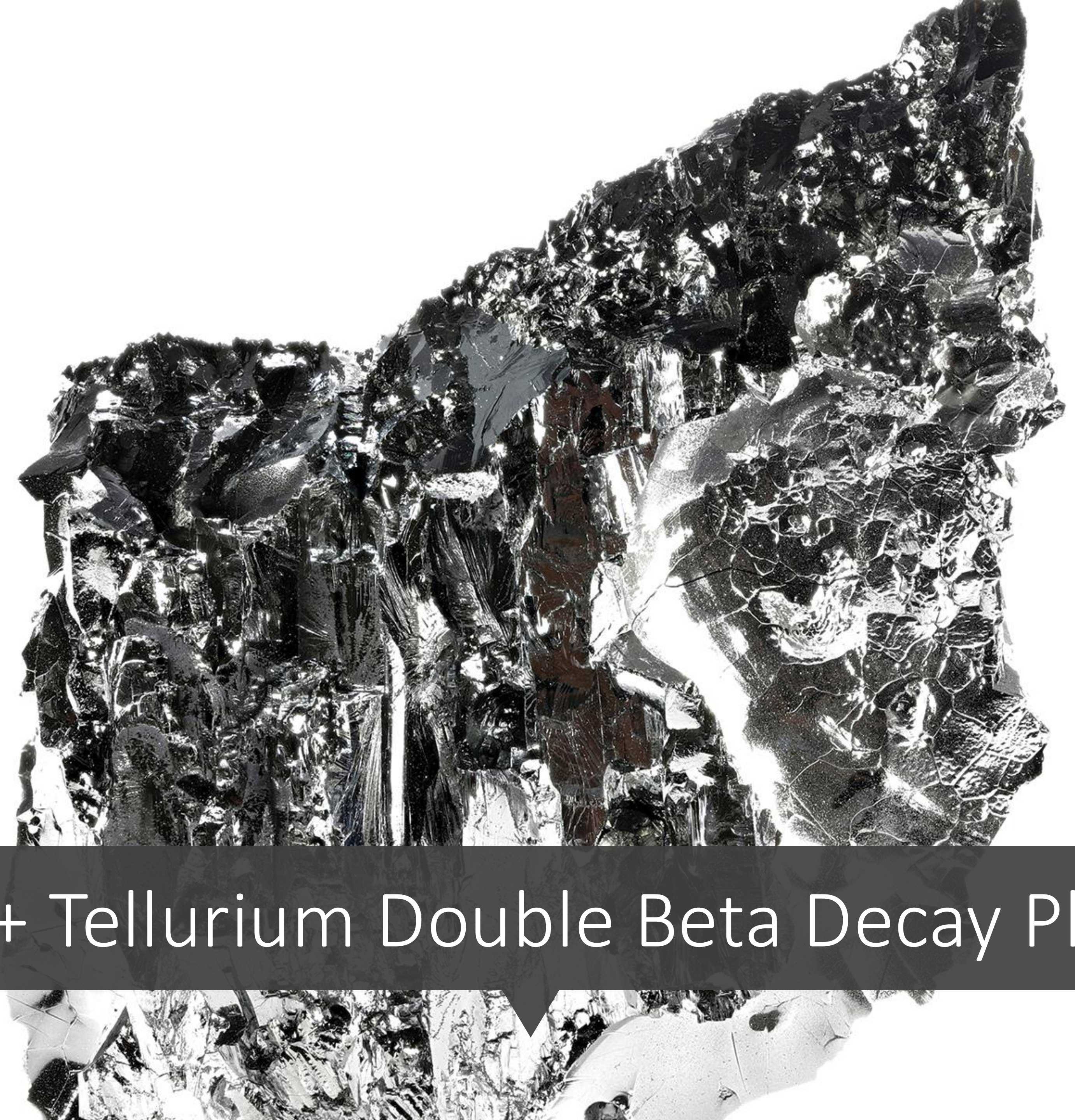


(α,n) classifier being retuned for 2.2 g/L PPO; will improve geo neutrino signal extraction – first results by end of 2024

The advantages of a well-understood detector with very low backgrounds…

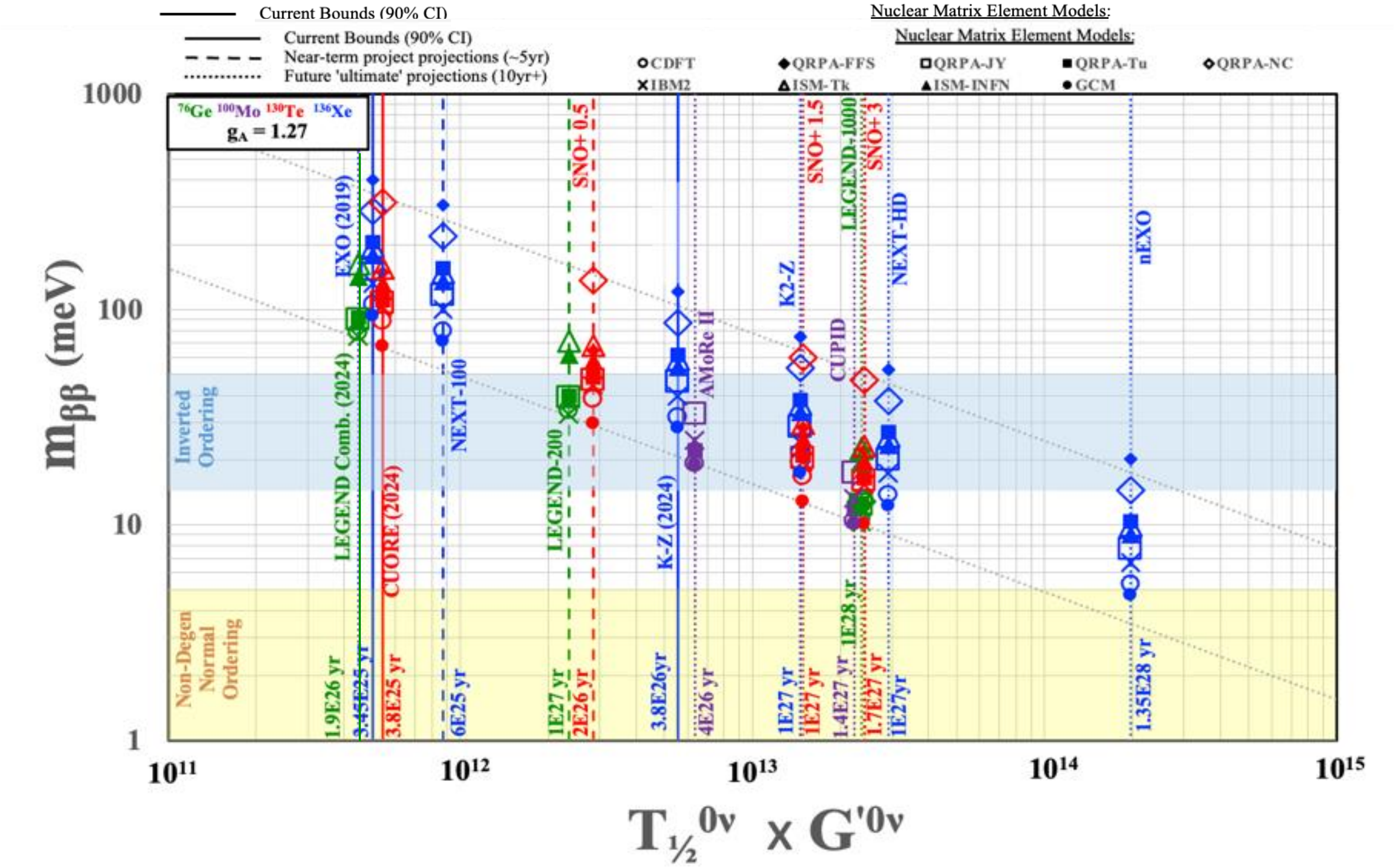
- are being demonstrated!
- enabling a wide variety of interesting physics topics to be studied – great for HQP training!

- With the detector performing well; with all background components being measured and constrained (most coming in at or below target levels), it looks promising for the final phase of SNO+…



SNO+ Tellurium Double Beta Decay Phase

DBD Sensitivity to $m_{\beta\beta}$

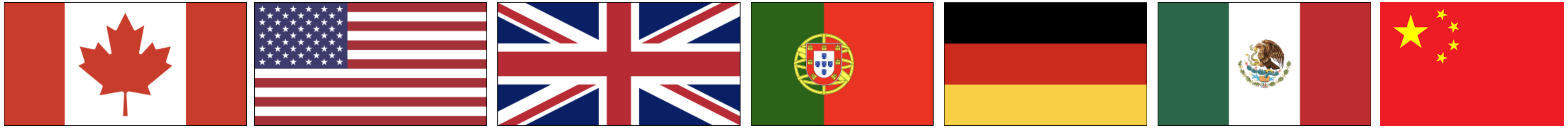


Summary

- SNO+ is an operating liquid scintillator neutrino detector filled with LAB + 2.2 g/L PPO (and now also 2.2 mg/L bis-MSB) and taking data
- Diverse program of neutrino physics is underway as the experiment prepares for the next phase – double beta decay search by adding natural tellurium to the scintillator
- Recent results:
  - Water Phase ^{8}B solar neutrinos with even lower backgrounds – paper submitted
  - Partial-fill reactor antineutrino oscillations – paper submitted
  - Full-fill reactor antineutrino oscillations measurements – presented
  - Geo neutrino flux (ultra-preliminary measurement) – presented
  - ^{8}B solar neutrino measurements: flux, spectrum, oscillation analysis – presented
  - CC ν_e capture on ^{13}C, never observed before – first indications presented

at Neutrino 2024


SNO+ 2023
EXIT
Physics

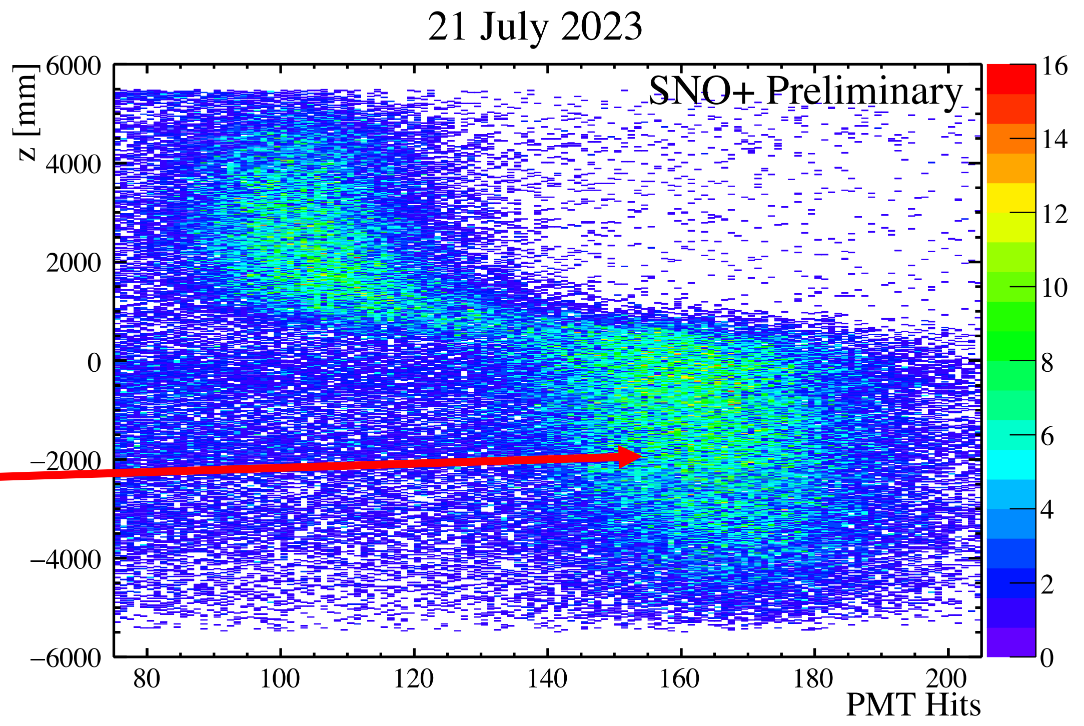


BACKUP

Recent addition of bis-MSB (and BHT)

- Recently added 2.2 mg/L bis-MSB to the liquid scintillator cocktail (plus a small amount of BHT, antioxidant) in preparation for SNO+ Te Double Beta Decay Phase
- Boosted light yield in the detector by ~1.7×

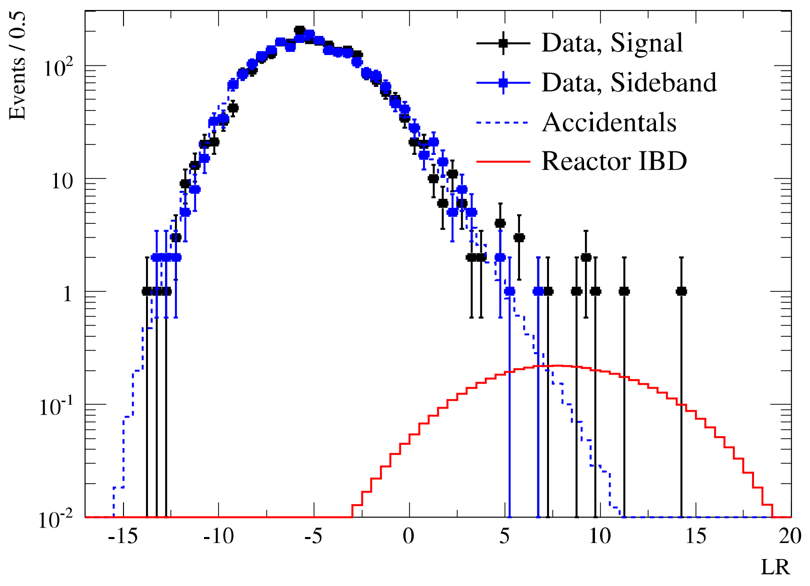
Plot on the right shows ^{210}Po events in detector versus z position after adding ~0.5 mg/L bis-MSB to the bottom of the detector

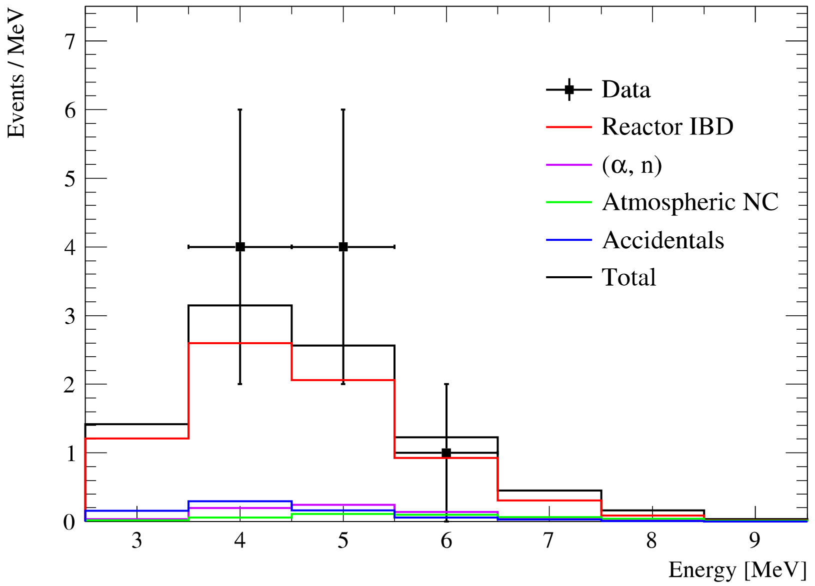


Antineutrino IBD Events in SNO+ Water? Yes!

Water Phase – Detection of IBD events (reactor antineutrinos) using pure water → this is a first

Two independent analyses – likelihood ratio and Boosted Decision Tree – both with 3σ detection significance; using event selection overlap + non-overlap, calculated combined discovery significance of 3.5σ



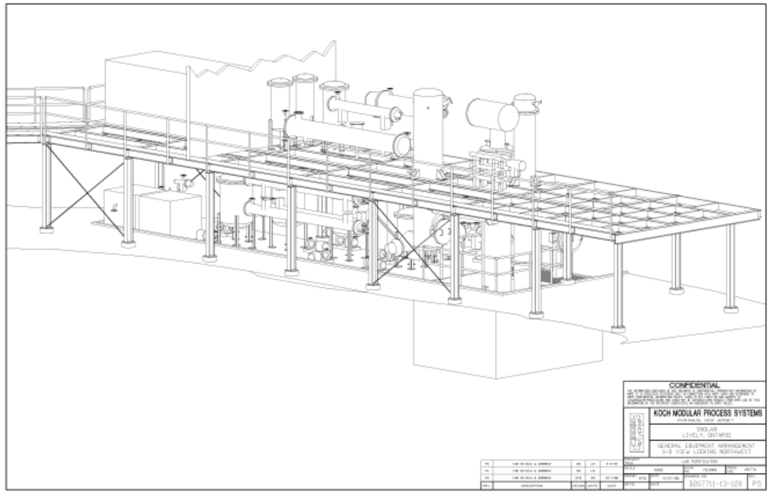


SNO+ Scintillator Purification Plant

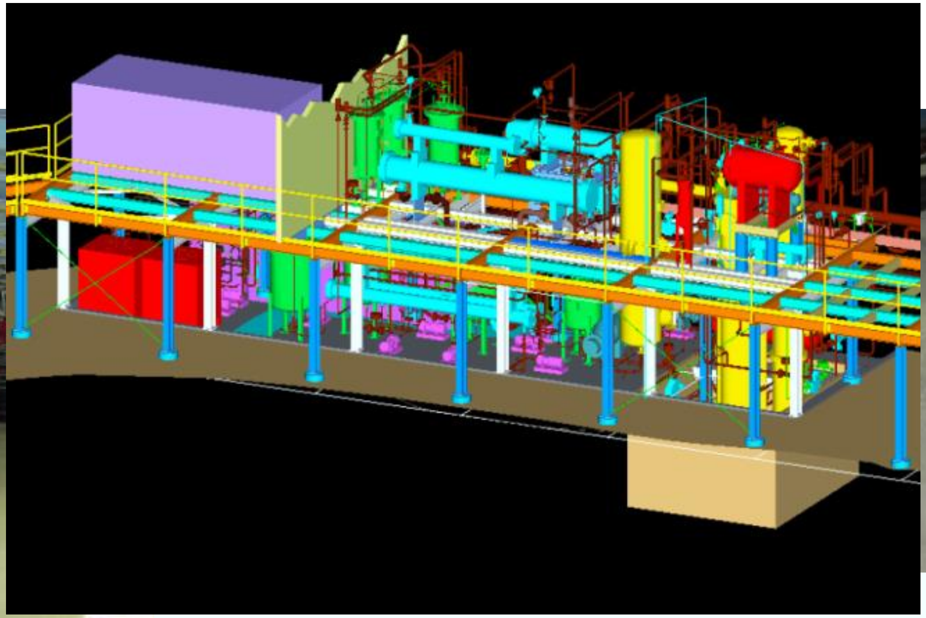
- reinforced mezzanine steel
- enlarged D2O pit “mining in a clean room”
- installed columns, vessels, heat exchangers, tank, pumps, valves, high-grade sanitary piping (orbital-welded, electropolished stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression

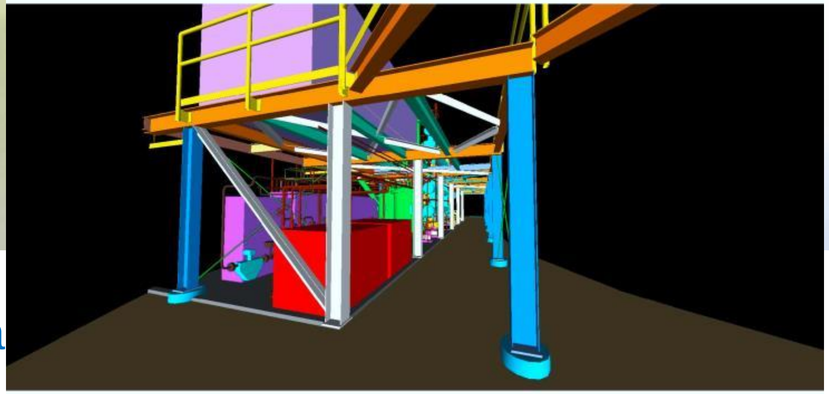
SNO heavy water purification system was here

SNO+ Scintillator Purification Plant



- rein
- enla
  clea
- inst
  hea
  pum
  san
  welded, electropolished
  stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression





SNO hea


SCINTILLATOR
SCINTILLATOR 1042
E-101

SNO+ upgrades also included

- Refurbishing the electronics
- Repair of many “dead” PMT bases
- All-new DAQ
- New cover gas system
- New calibration systems capable of deploying in LAB scintillator
- New *in-situ* injected LED/laser light calibration system
- Calibration system cameras (for photogrammetry)

…in addition to the hold-down ropes and the scintillator plant