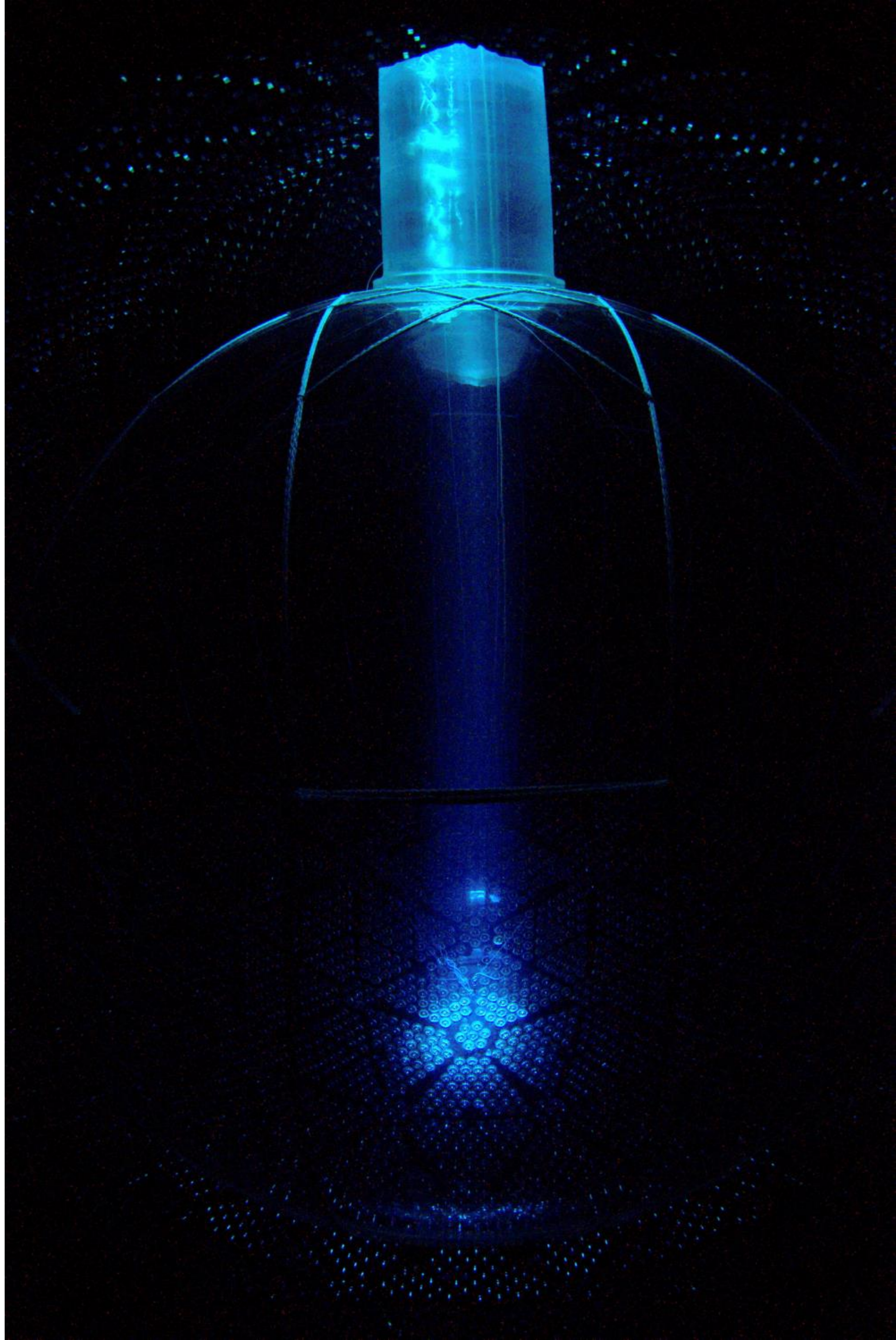
SNO+

International Symposium on Neutrino Physics and Beyond (NPB 2024)

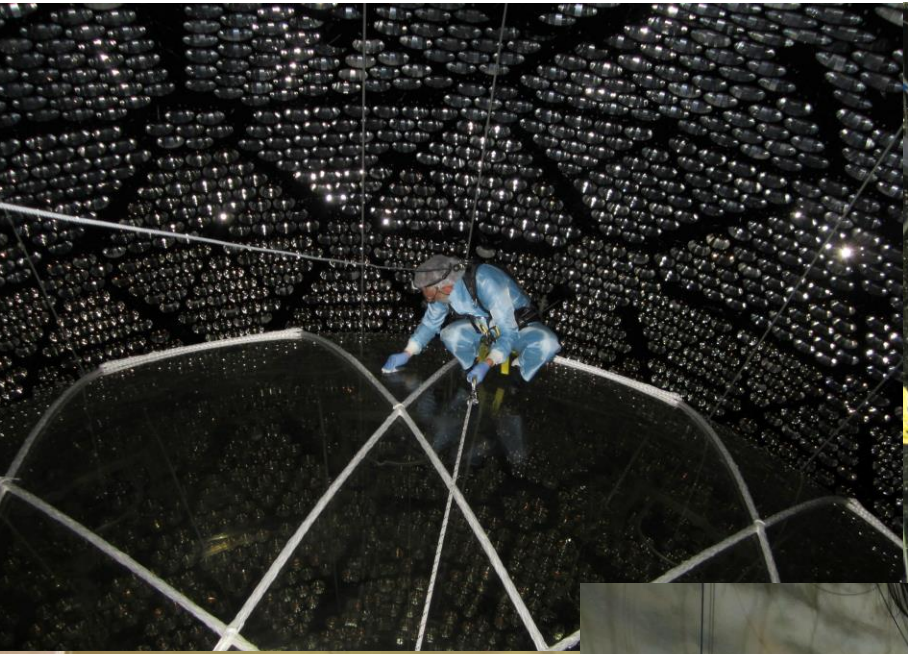


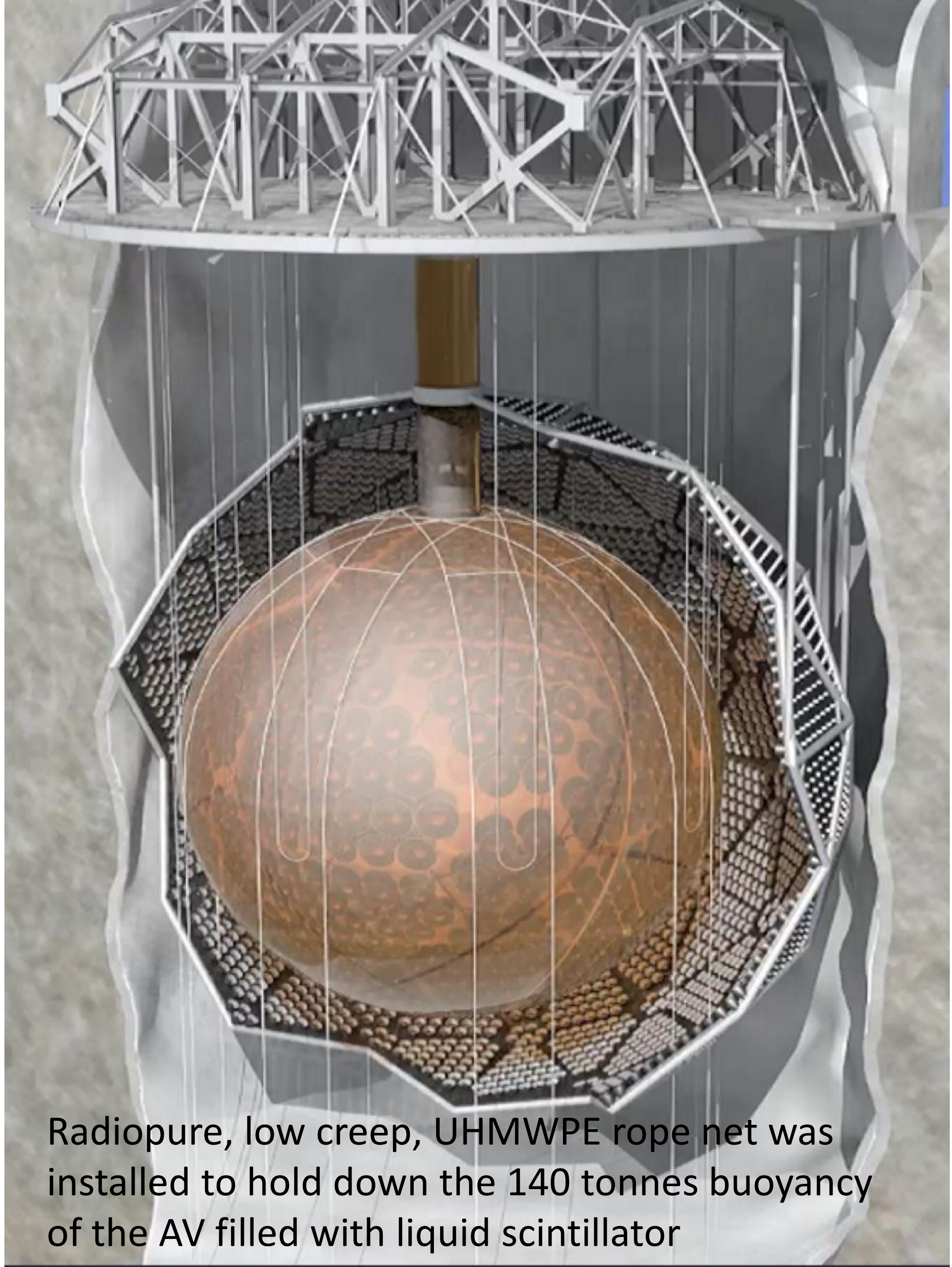
Mark Chen

Queen's University and CIFAR

February 20, 2024

SNO+ is the Sudbury Neutrino Observatory Filled with Liquid Scintillator





Radiopure, low creep, UHMWPE rope net was installed to hold down the 140 tonnes buoyancy of the AV filled with liquid scintillator

Repairs and Upgrades

Historically significant objects sometimes need a few repairs…

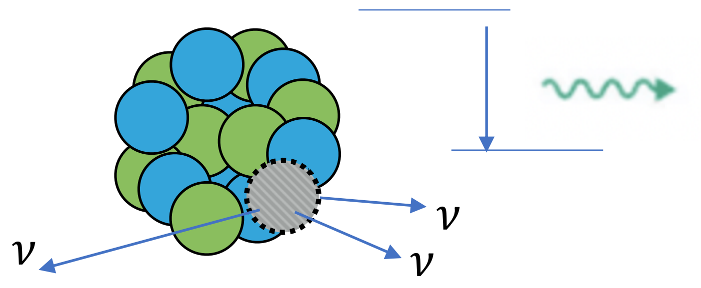
- SNO Cavity floor liner had been badly torn at the end of SNO; had to be remade (during SNO+ hold-down anchor installation)
- Anchor plate installation involved *drilling* into concrete and rock *inside an ultra-low background neutrino detector*
- Submersible pump that drained the SNO AV had self-destructed, covering the inner AV bottom with dirty oil
- SNO Cavity wall liner had many leaks – SNO+ had to find these pinhole leaks paddling around in the Cavity in a raft, in low-light conditions, using multiple leak hunting techniques…many months of effort!

- After all of these interventions, would SNO+ still have low backgrounds?

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

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

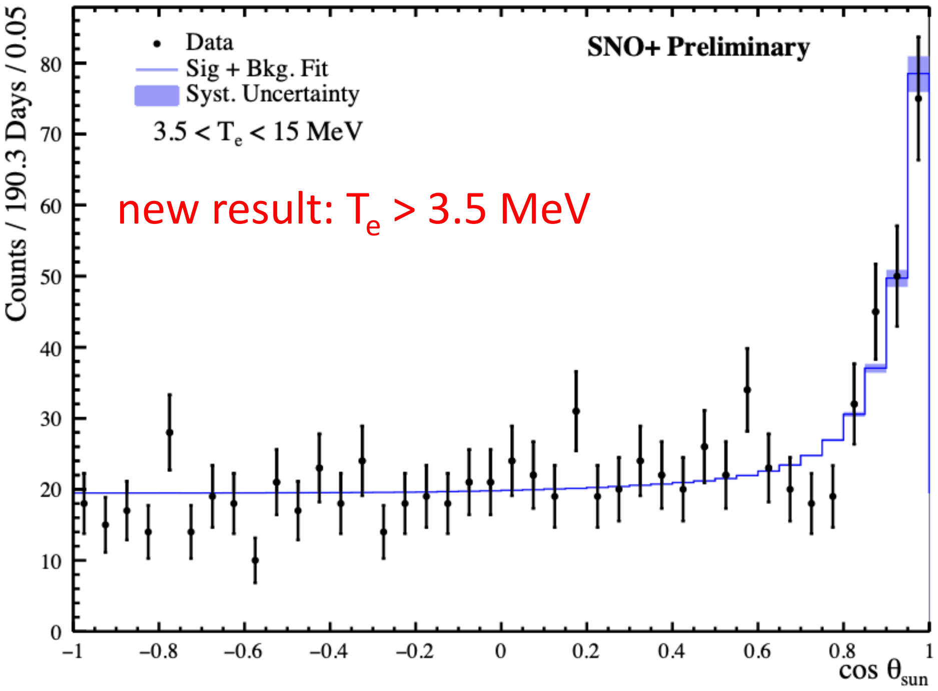
PHYSICAL REVIEW D **99**, 012012 (2019)

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

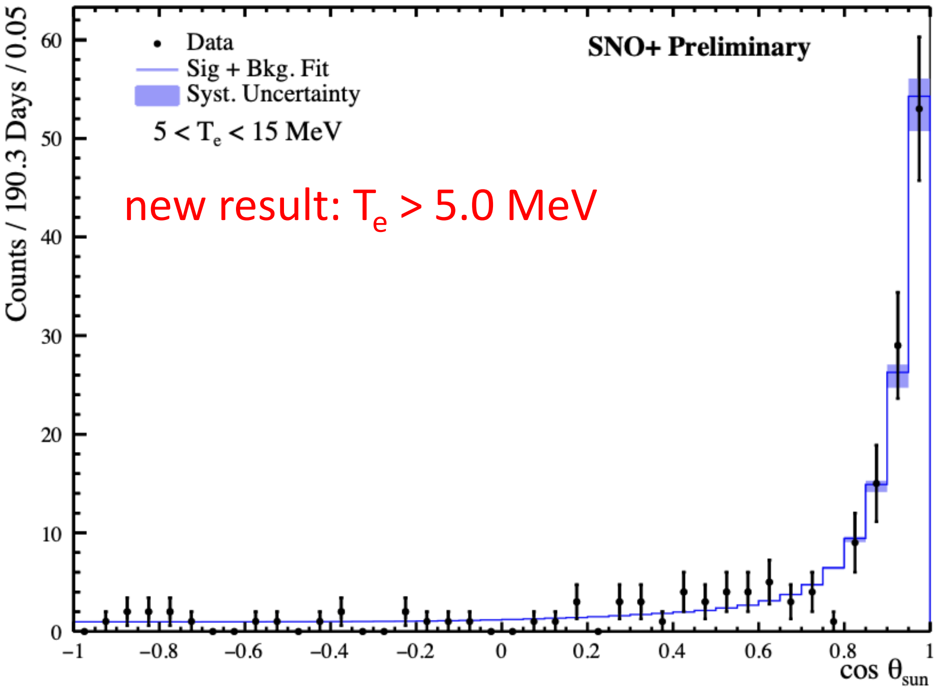
  - now with *even lower backgrounds*

- 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)

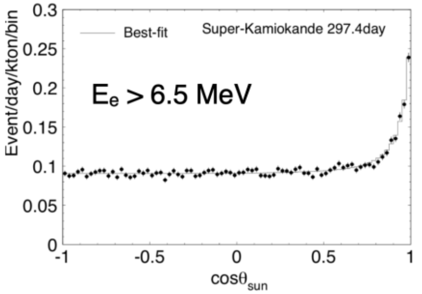
^{8}B solar neutrinos in SNO+ Water Phase



new result: T_e > 3.5 MeV



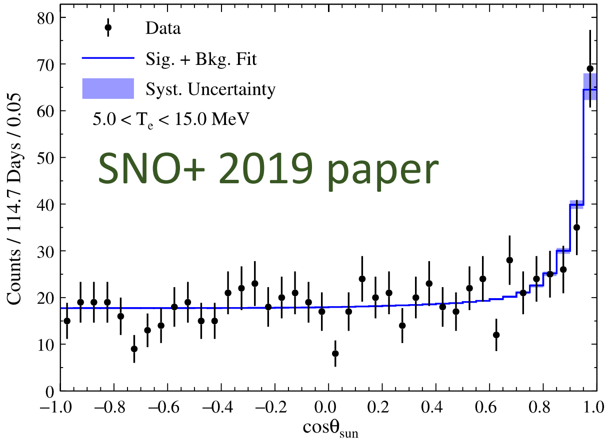
new result: T_e > 5.0 MeV



first Super-K result, for comparison

same 5.0 MeV threshold

Our upcoming paper includes data from the extended water phase, with ~1/10 Rn levels (new SNO+ cover gas system)



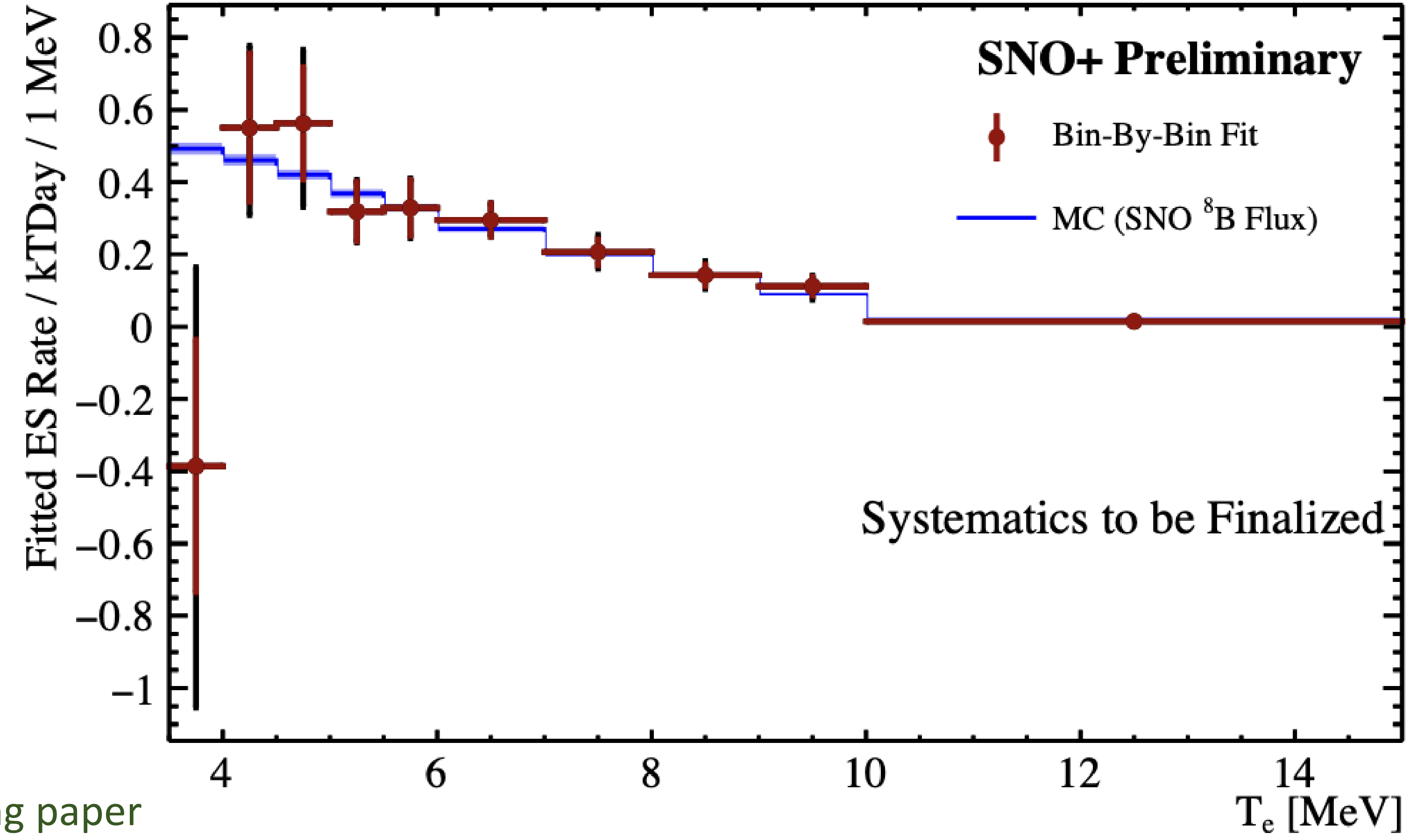
SNO+ 2019 paper

Answer to the question: did we succeed to restore SNO+ as a low-background detector? YES!

Deep underground location 6000 m.w.e. also helps to greatly suppress cosmogenic backgrounds.

SNO+ Water Phase ^{8}B Solar Neutrino Energy Spectrum

result as shown at Neutrino 2022



Will be in our upcoming paper

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

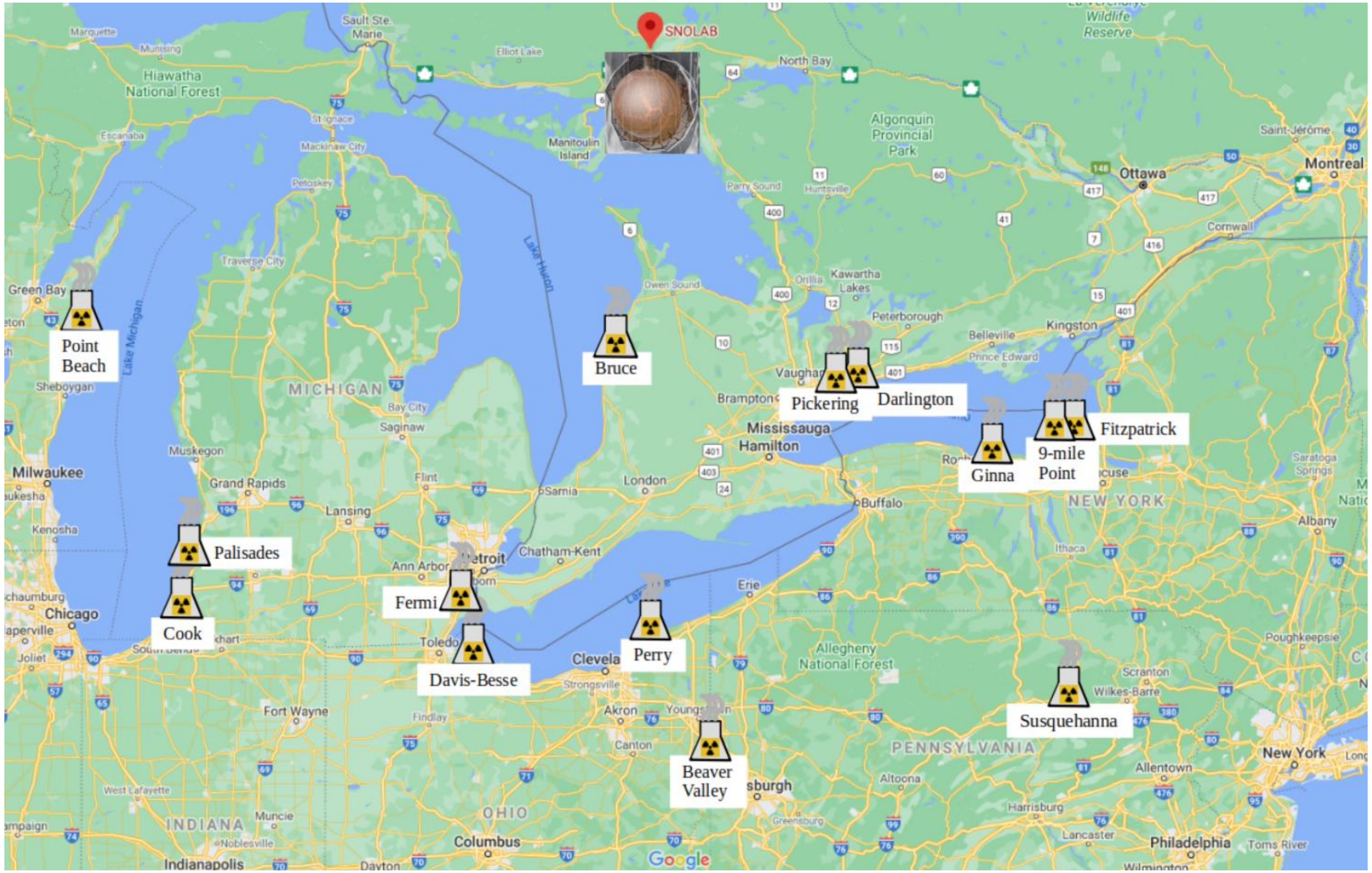
Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+

240 and 340 km away

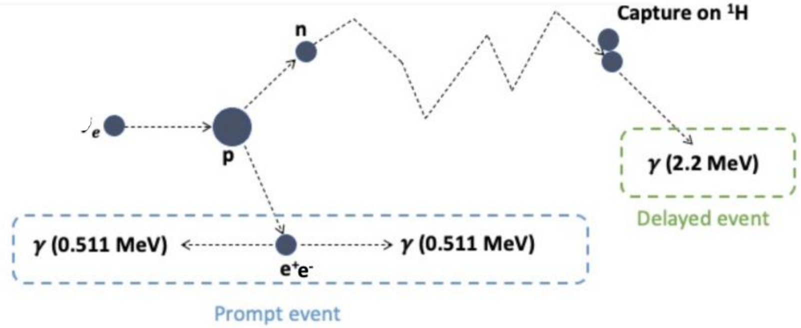
technical papers

- 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)

Reactor Antineutrinos in SNO+



Inverse Beta Decay (IBD)



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

Coincidence event

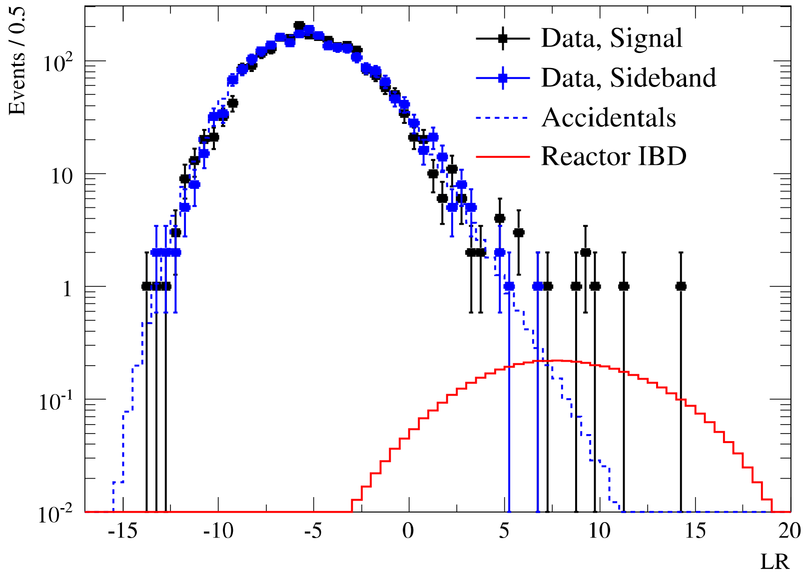
Prompt – positron kinetic energy (several MeV) plus 1.022 MeV from annihilation γ's

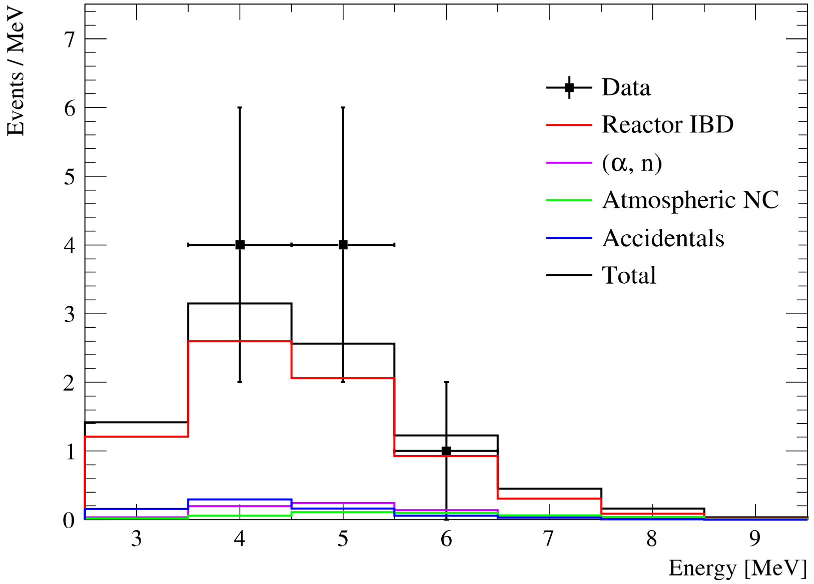
Delayed – neutron capture 2.2 MeV γ

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





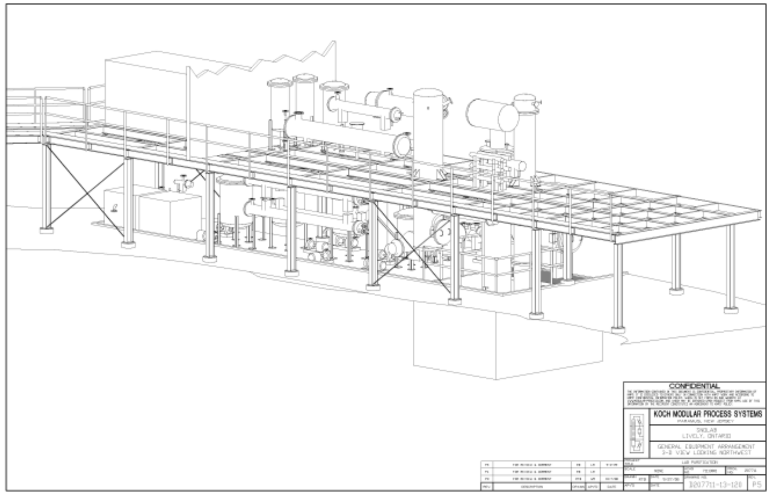
SNO+ Scintillator Purification Plant

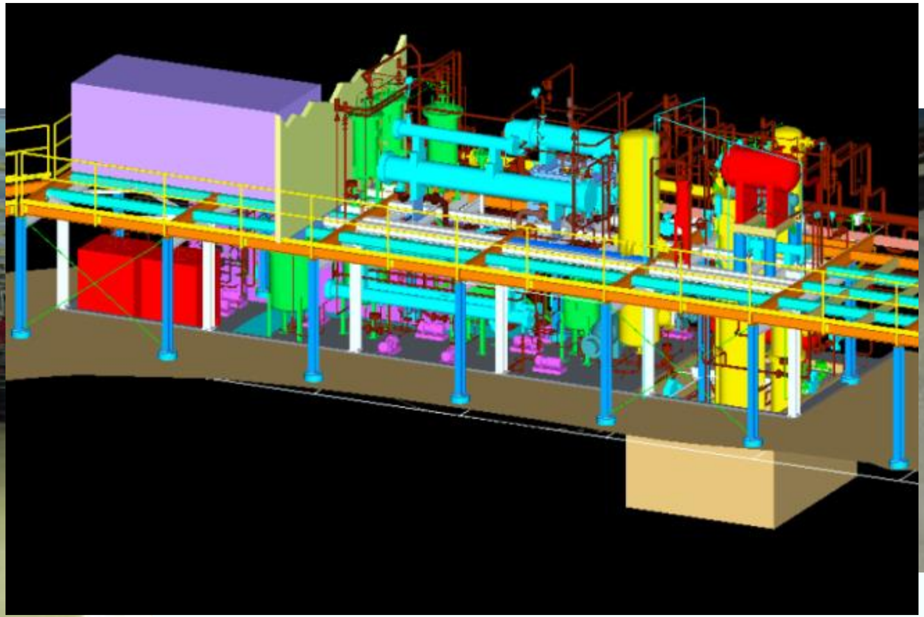
- reinforced mezzanine steel
- enlarged D2O pit "mining in a clean room"
- installed columns, vessels, heat exchangers, tank, pumps, valves, high-grade sanitary piping (orbital-welded, electropolished stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)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

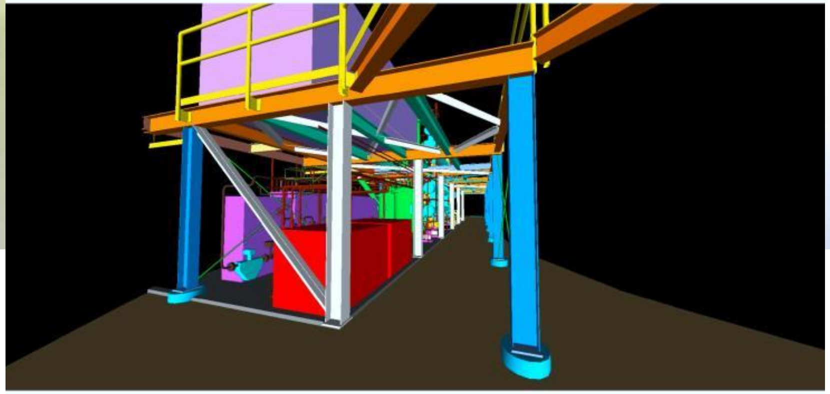
SNO heavy water purification system was here

SNO+ Scintillator Purification Plant

- rei
- mac
  “m
- ins
  ves
  tanl
  gra
  (orl
  electropolished stainless
  steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression









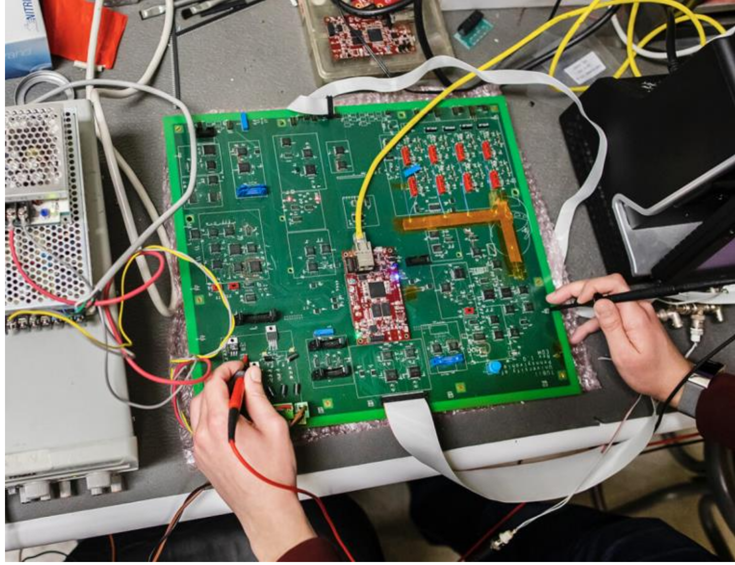


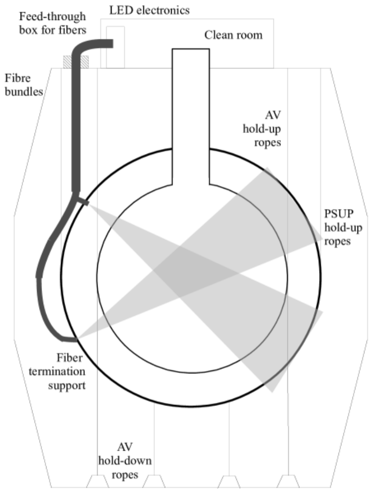
SCINTILLATOR
E-101

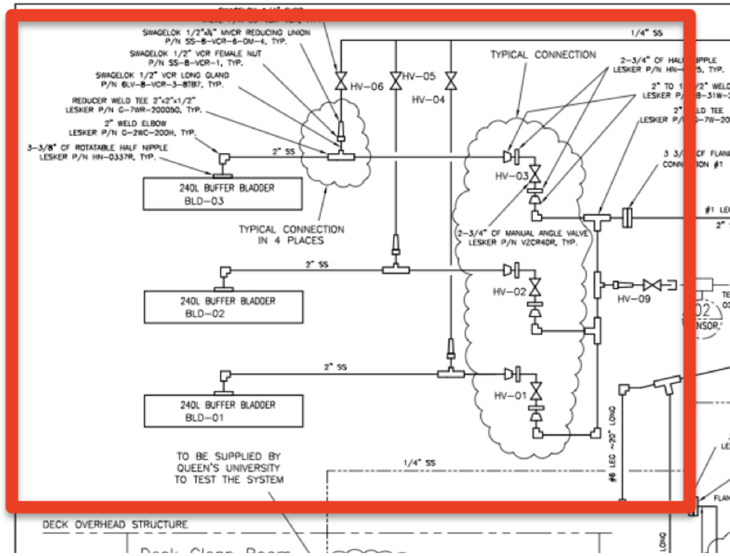
SNO+ upgrades also included

- 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







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

$(4.7\pm1.2)\times10^{-17}\ g_U/g_{LAB}$

^{212}BiPo delayed coincidences for Th chain

$(5.3\pm1.5)\times10^{-17}\ g_{Th}/g_{LAB}$

meeting SNO+ background targets (for double beta decay)

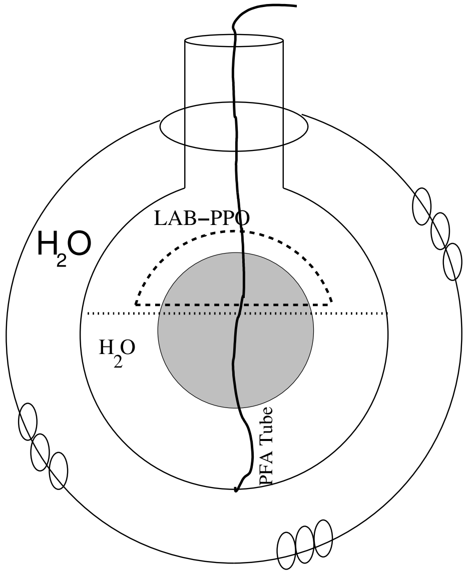
- Optical properties of LS 👍
- Also physics from SNO+ partial fill…

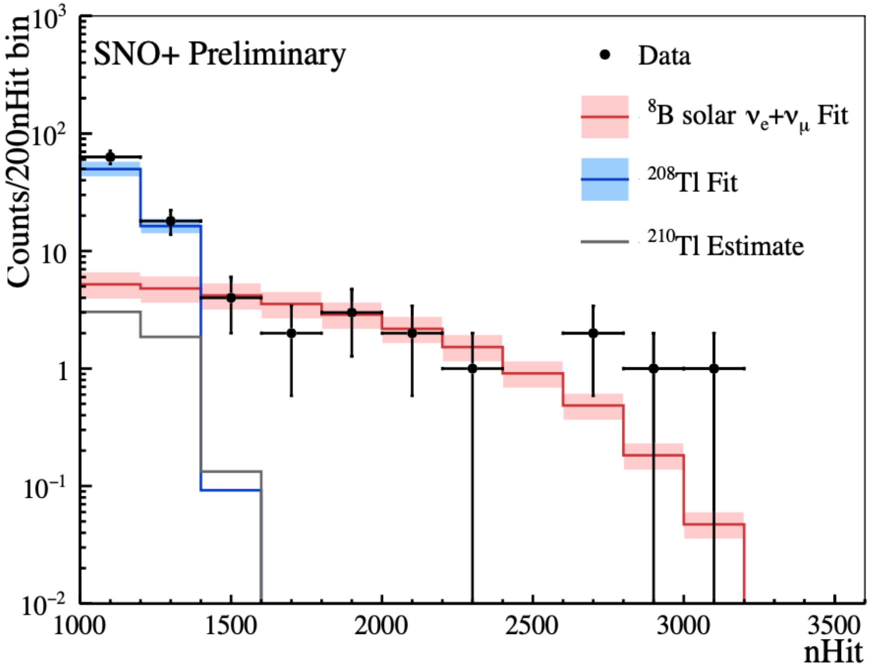
Partial-fill data taken in 2020

Physics with Partial-Fill Scintillator

^{8}B solar neutrinos in partial-fill scintillator

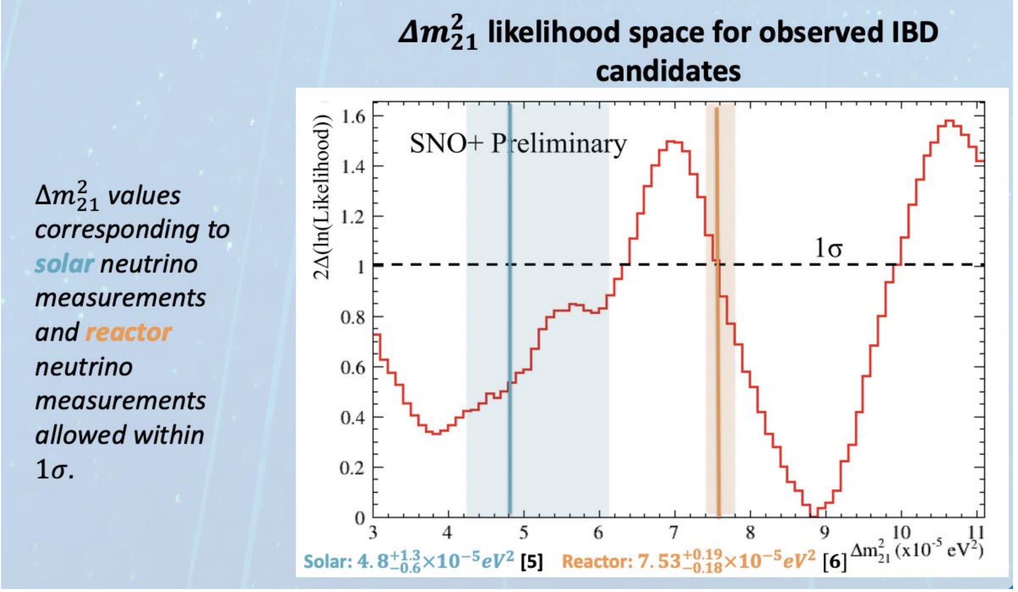
- demonstrates SNO+ LS solar neutrino detection, even in an imperfect detector configuration





Reactor antineutrinos in partial-fill scintillator

- showcasing potential for Δm^2_{12} with full LS



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

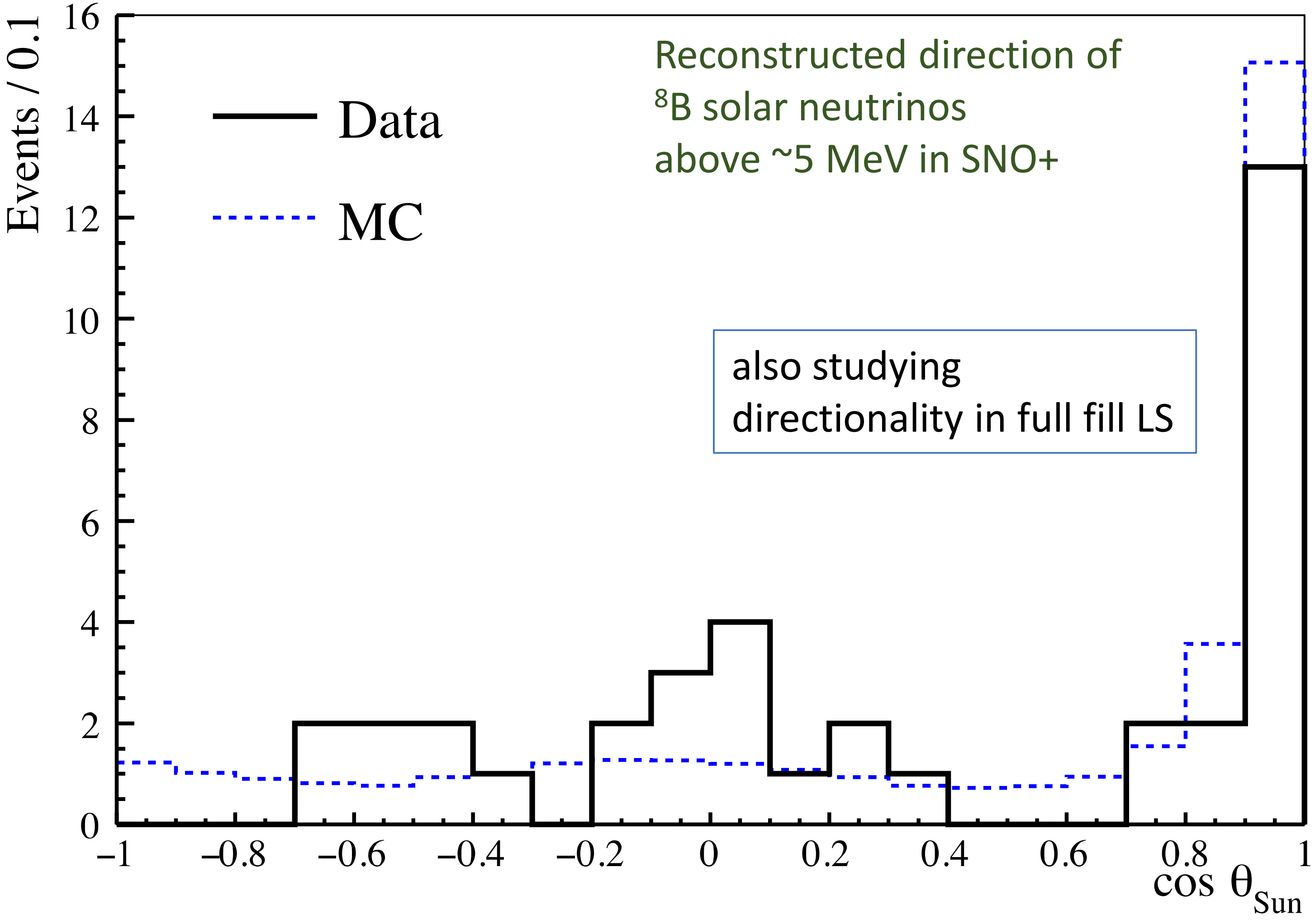
- Borexino has published the observation of a correlation between early PMT hits in the forward direction caused by the Cherenkov light produced by ^{7}Be solar neutrinos in liquid scintillator

  "Correlated and Integrated Directionality"

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

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

Accepted for publication in *Phys. Rev. D*



SNO+ Scintillator Fill Completed during the pandemic

- Deliveries of LAB from CEPSA (Bécancour, QC) to SNOLAB
- Transportation of LAB from surface to underground, coordinating with Vale, shipping railcars underground
- Distillation of LAB
- Water extraction and secondary distillation of PPO
- Nitrogen stripping
- Simultaneous filling of AV with purified LS and draining of water
- Nearly 5,000 QA samples analyzed (with assistance from the SNOLAB Scientific Support Group) to verify the quality of the process to approve it before sending purified LS to the AV
- After completion of “bulk” fill, topped up the PPO concentration in the detector LS to 2.2 g/L

Monumental effort by SNO+ and SNOLAB during the pandemic!

April 2022, scintillator operations concluded and we started the…

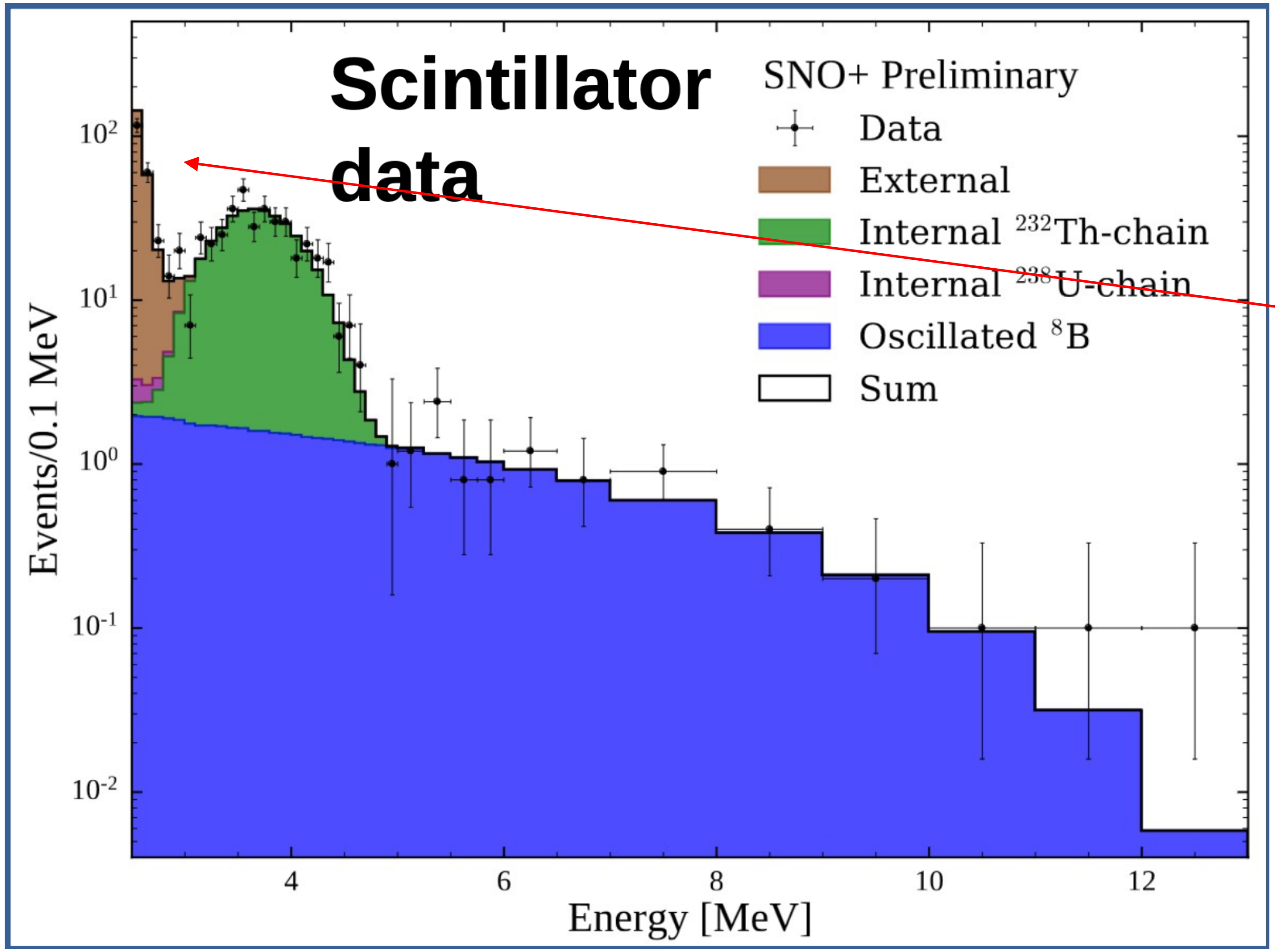
SNO+ Scintillator Phase

Physics Goals in the Scintillator Phase

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

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

Preliminary data as shown at TAUP 2023



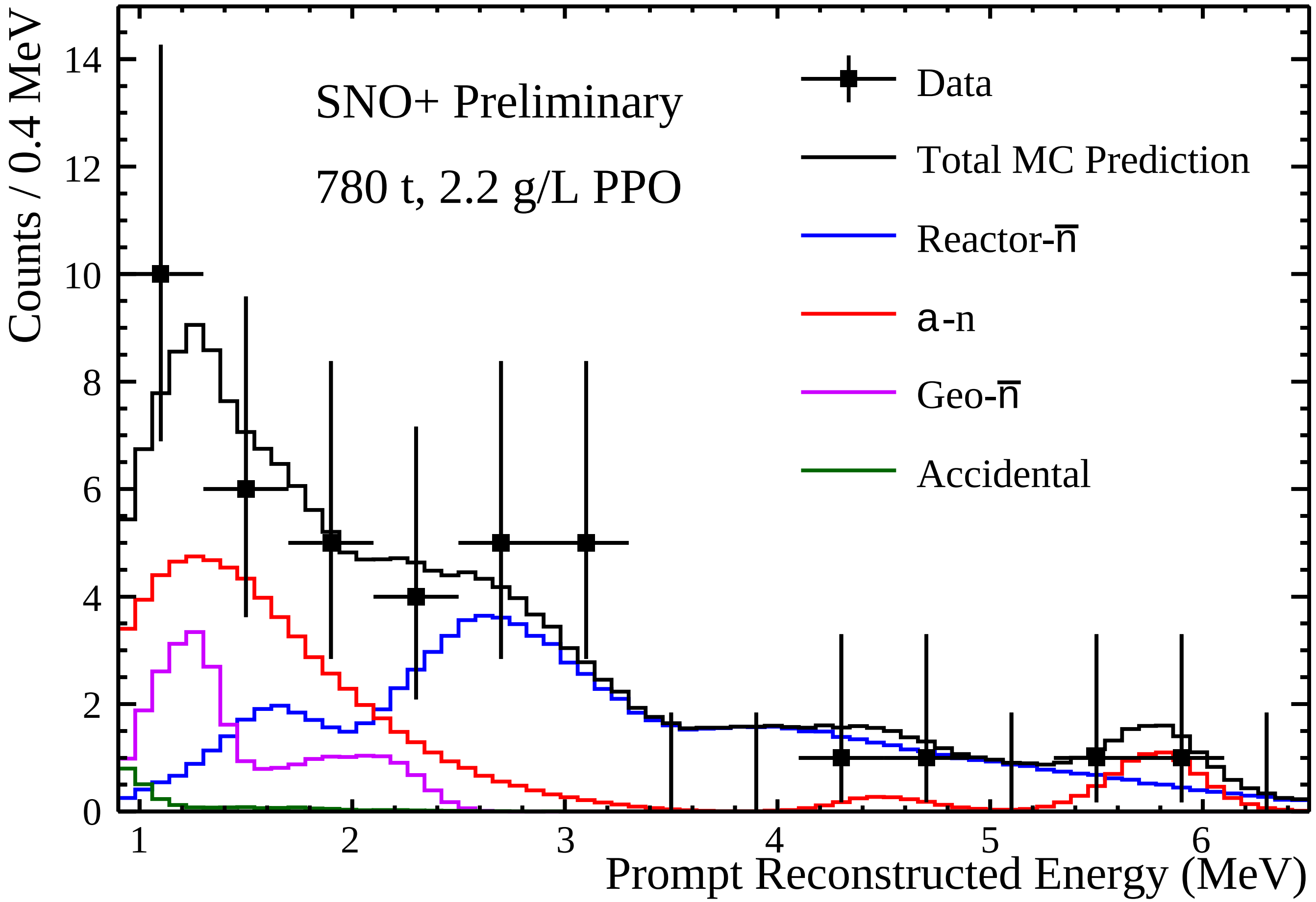
Internal Th backgrounds between 3 and 4 MeV – background rejection using directionality/multi-site being studied

N.B. Plot shows data with large fiducial volume

In a smaller fiducial volume (R < 3.3 m), external backgrounds are negligible and ^{8}B solar neutrinos are being detected down to below 2.5 MeV

SNO+ Scintillator Phase: Antineutrinos in Full LS

Preliminary data as shown at TAUP 2023



SNO+ is detecting geo neutrinos!!

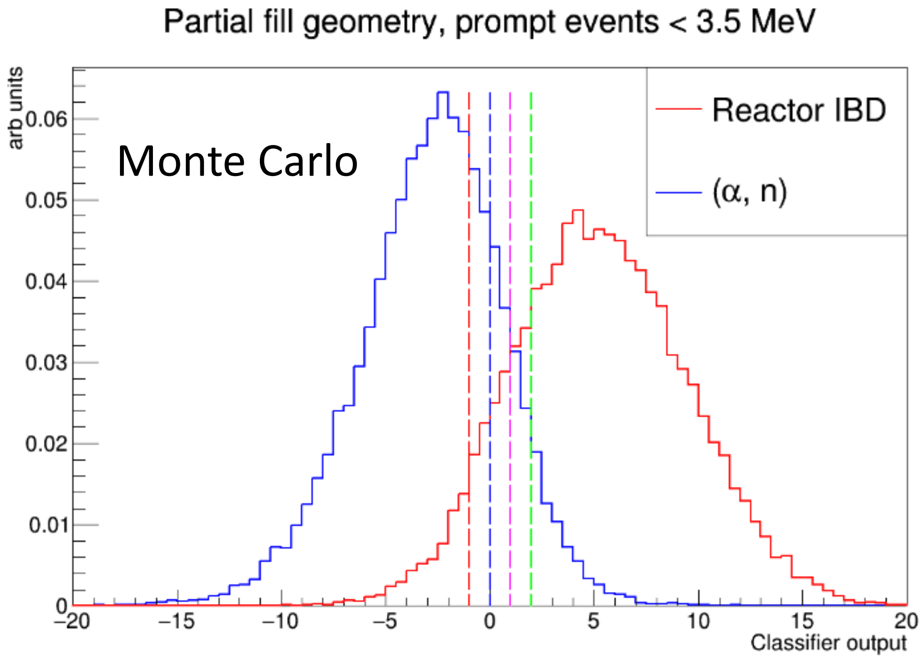
<u>IBD events from $\bar{\nu}_e$</u> In the plot,

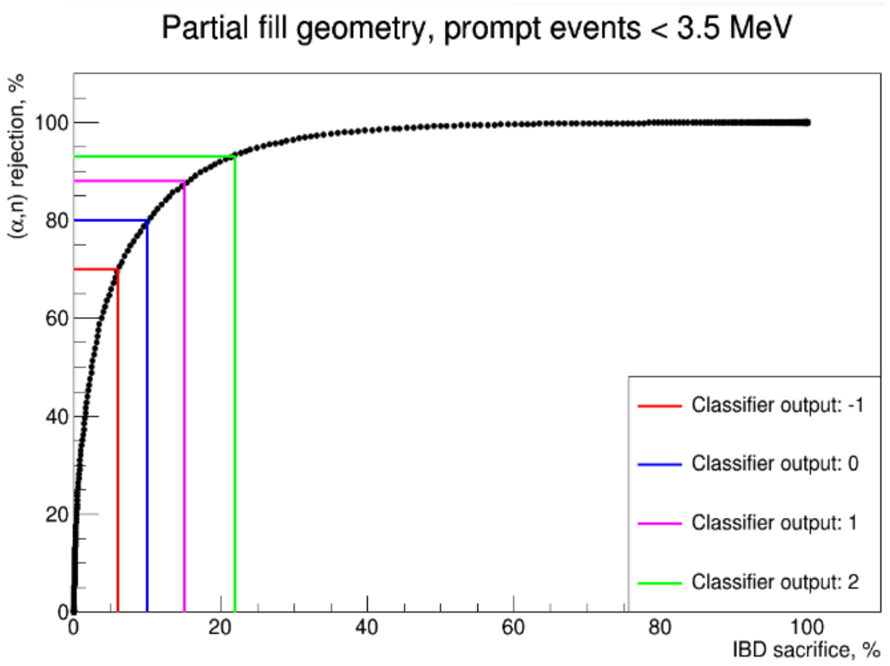
(α, n) events don' t yet include classifier cut rejection

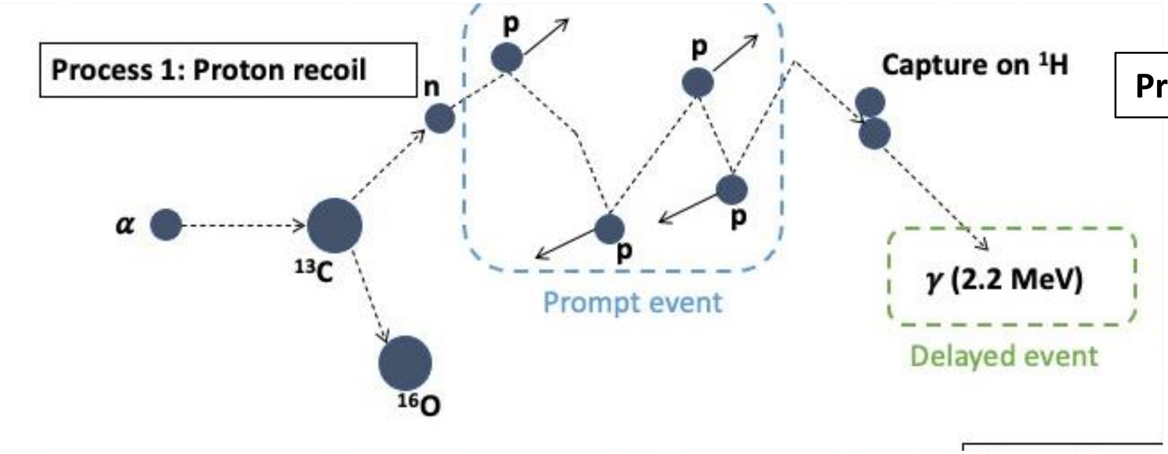
(being retuned for 2.2 g/L PPO

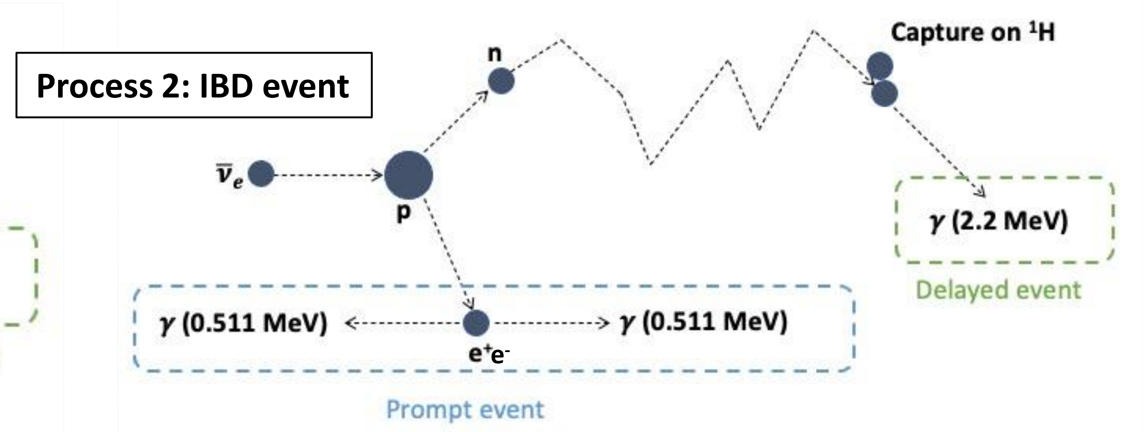
proton-recoil timing)

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

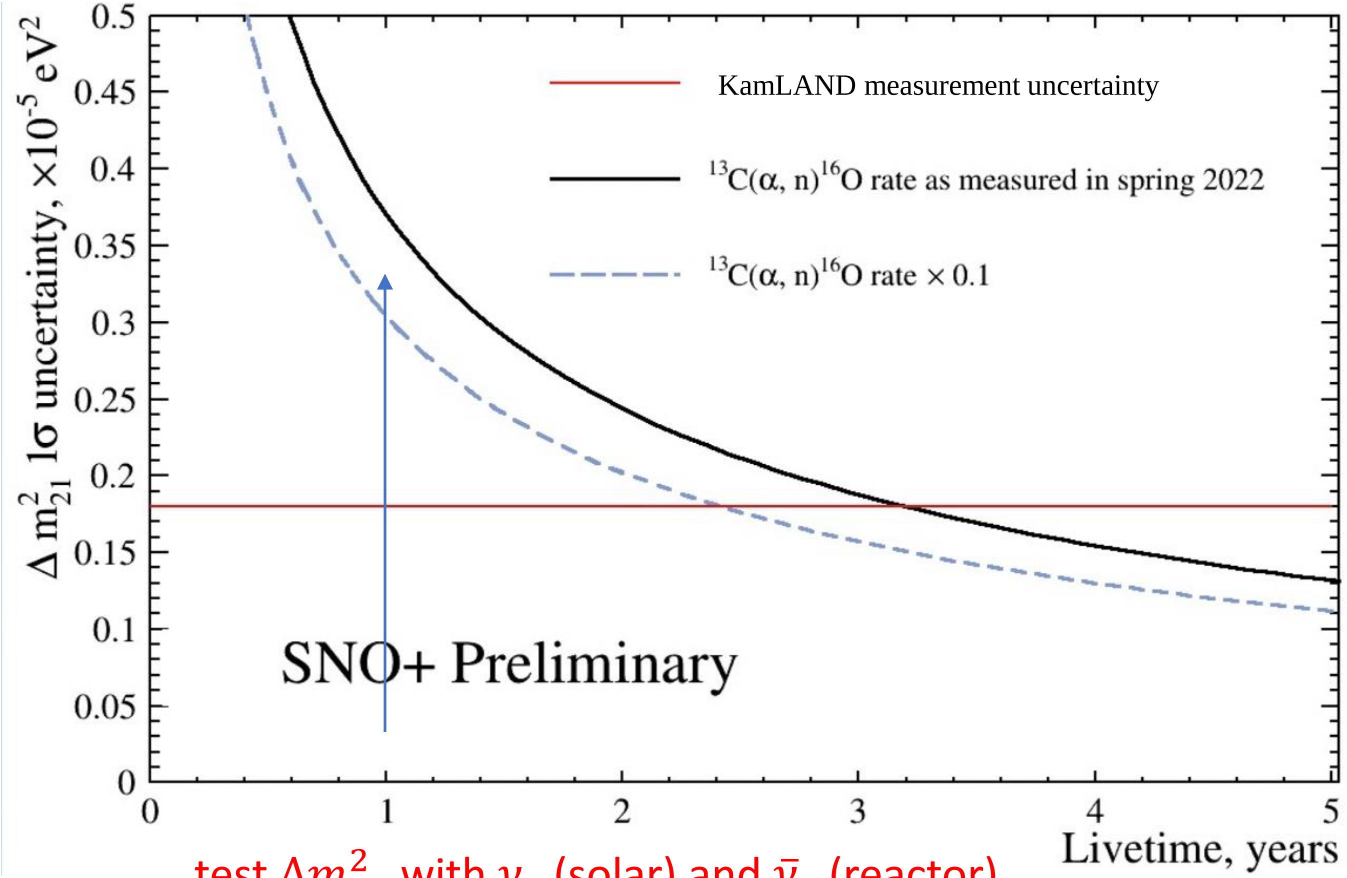


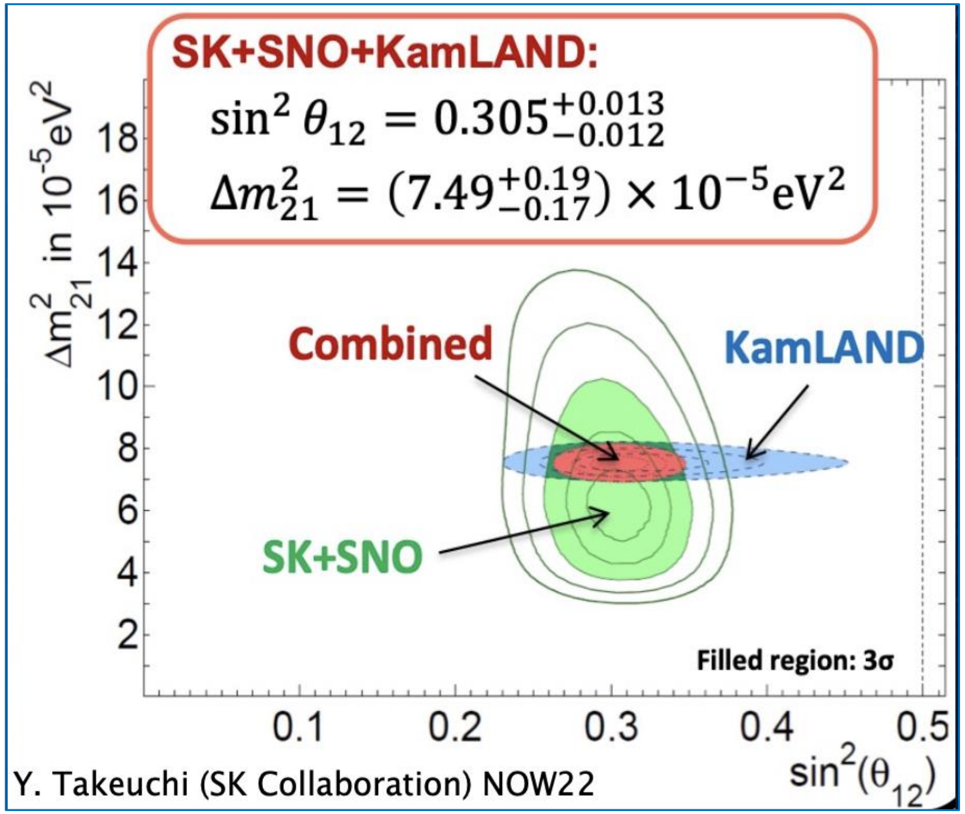






Objectives for SNO+ Scintillator Phase: Reactor Antineutrinos Δm^2_{12}



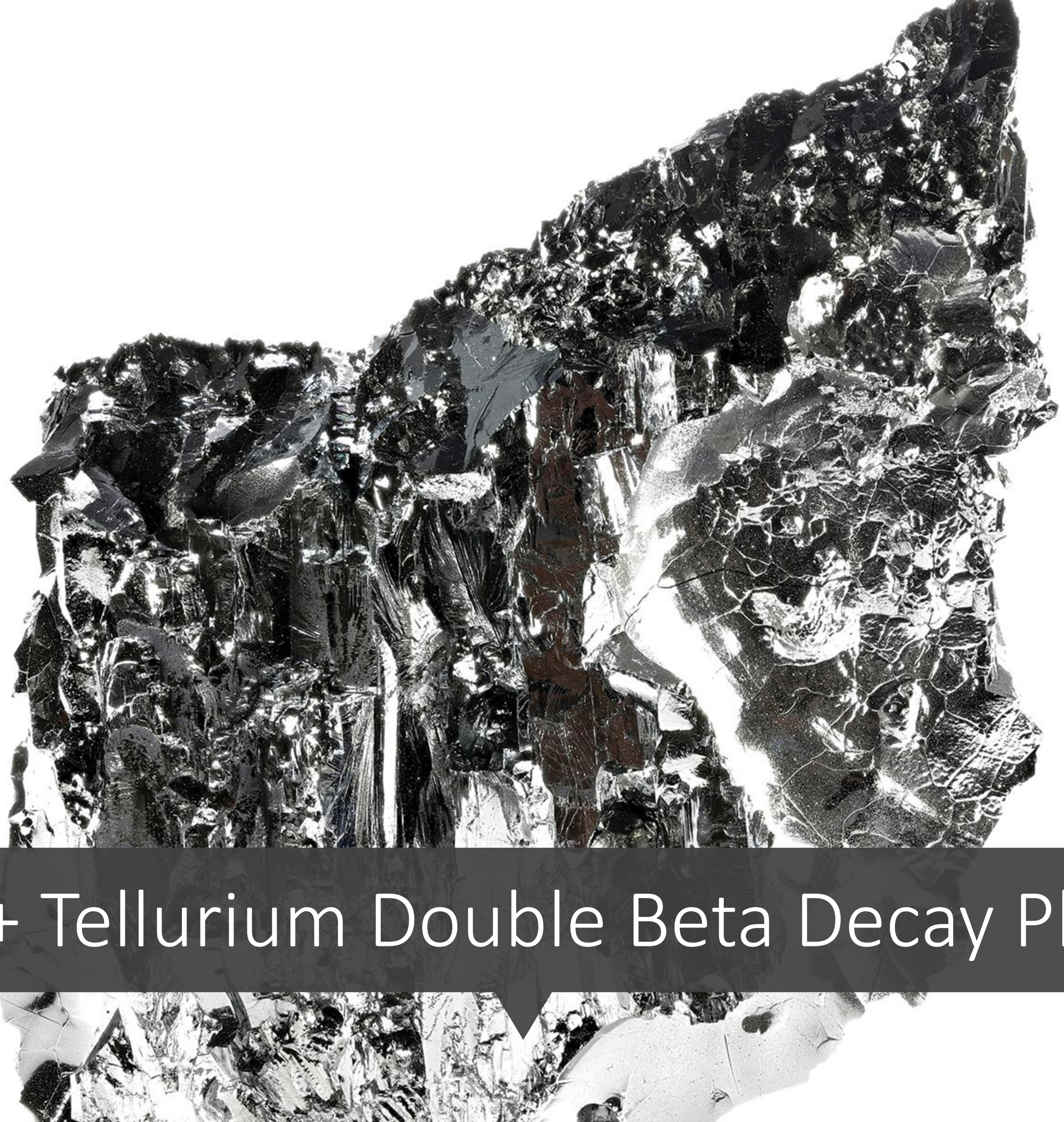


test Δm^2_{12} with ν_e (solar) and $\bar{\nu}_e$ (reactor)
can easily distinguish 5.0 from 7.5 ($\times 10^{-5}$ eV^2)

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

- are being demonstrated!
- and allows SNO+ to pursue a physics program with many interesting topics.

- 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+…

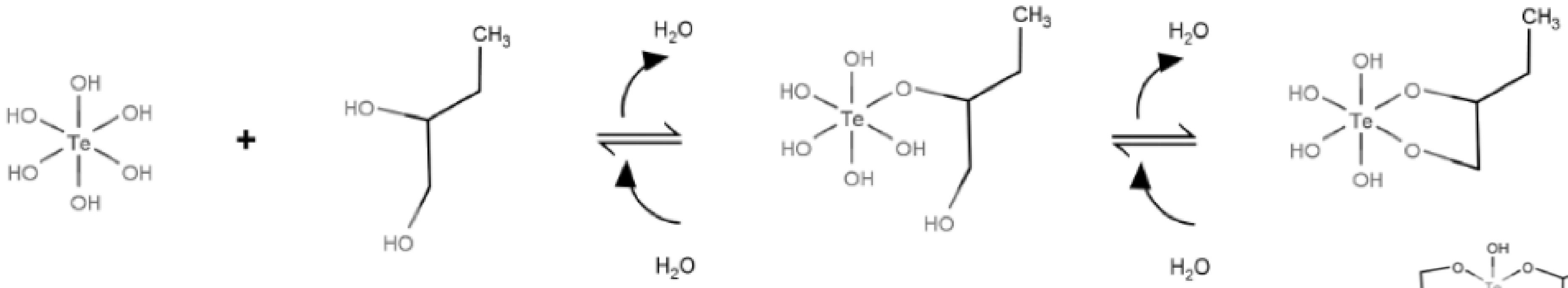


SNO+ Tellurium Double Beta Decay Phase

Neutrinoless Double Beta Decay in SNO+ with Tellurium-Loaded Liquid Scintillator

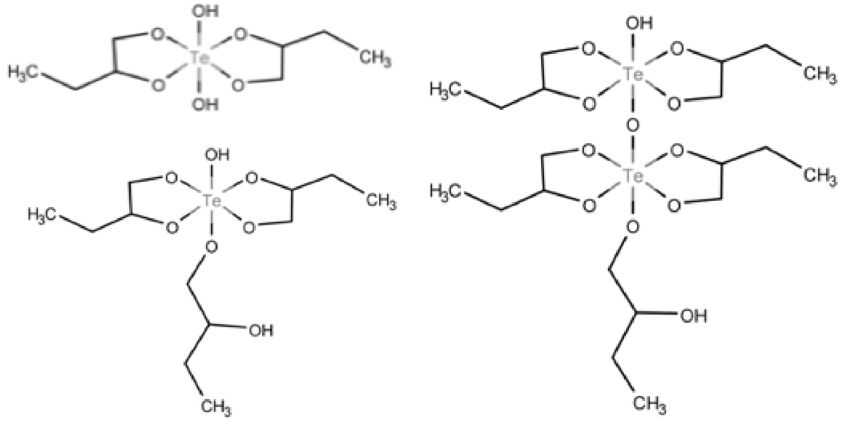
Principal goal: economical, scalable approach to $0\nu\beta\beta$; achieving sensitivity to $m_{\beta\beta}$ in the parameter space corresponding to the Inverted Neutrino Mass Ordering…*and beyond*

^{130}Te has 34% natural abundance = does not require costly or logistically difficult procurement of enriched isotope



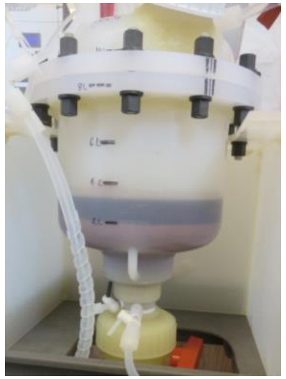
"Telluric Acid (TeA)" "1,2-Butanediol"

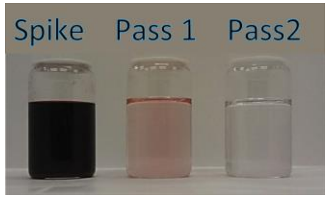
leading to tellurium-diol complexes that dissolve in LS



Novel Tellurium Purification and Tellurium Loading Techniques Pioneered by SNO+

Te purification technique established





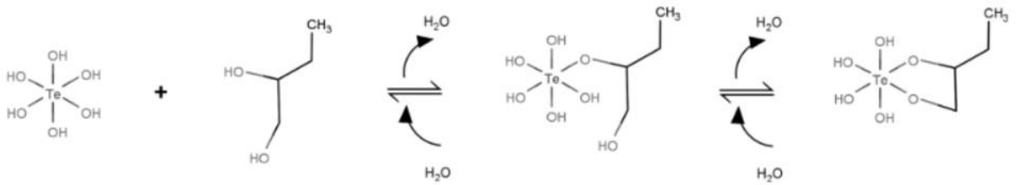
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 795, 21 September 2015, Pages 132-139

Purification of telluric acid for SNO+ neutrinoless double-beta decay search

S. Hans [a,1], R. Rosero [a,1], L. Hu [a,1], O. Chkvorets [b], W.T. Chan [a,1], S. Guan [a,1], W. Beriguete [a,1], A. Wright [d], R. Ford [c], M.C. Chen [d], S. Biller [e], M. Yeh [a,1]

Practical, stable Te loading method established



Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

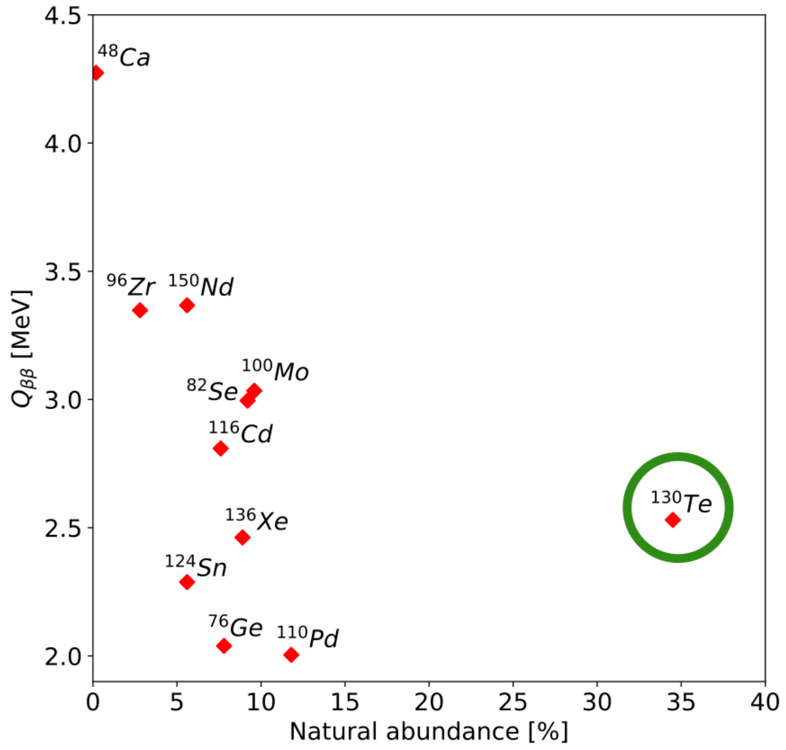
journal homepage: www.elsevier.com/locate/nima

Full Length Article

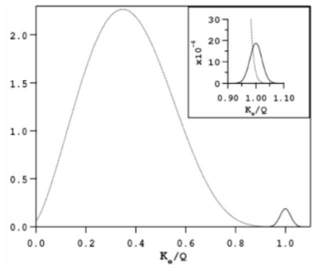
A method to load tellurium in liquid scintillator for the study of neutrinoless double beta decay

D.J. Auty [a], D. Bartlett [b], S.D. Biller [c,*], D. Chauhan [f,b], M. Chen [b], O. Chkvorets [d], S. Connolly [b], X. Dai [b], E. Fletcher [b], K. Frankiewicz [e], D. Gooding [e], C. Grant [e], S. Hall [f], D. Horne [b], S. Hans [i], B. Hreljac [b], T. Kaptanoglu [g,h], B. Krar [b], C. Kraus [d,f], T. Kroupová [c,g], I. Lam [b], Y. Liu [b], S. Maguire [i], C. Miller [b], S. Manecki [f,b], R. Rosero [i], L. Segui [c], M.K. Sharma [a], S. Tacchino [f], B. Tam [b], L. Tian [b], J.G.C. Veinot [a], S.C. Walton [d], J.J. Weigand [j], A. Wright [b,k], M. Yeh [i], T. Zhao [b]

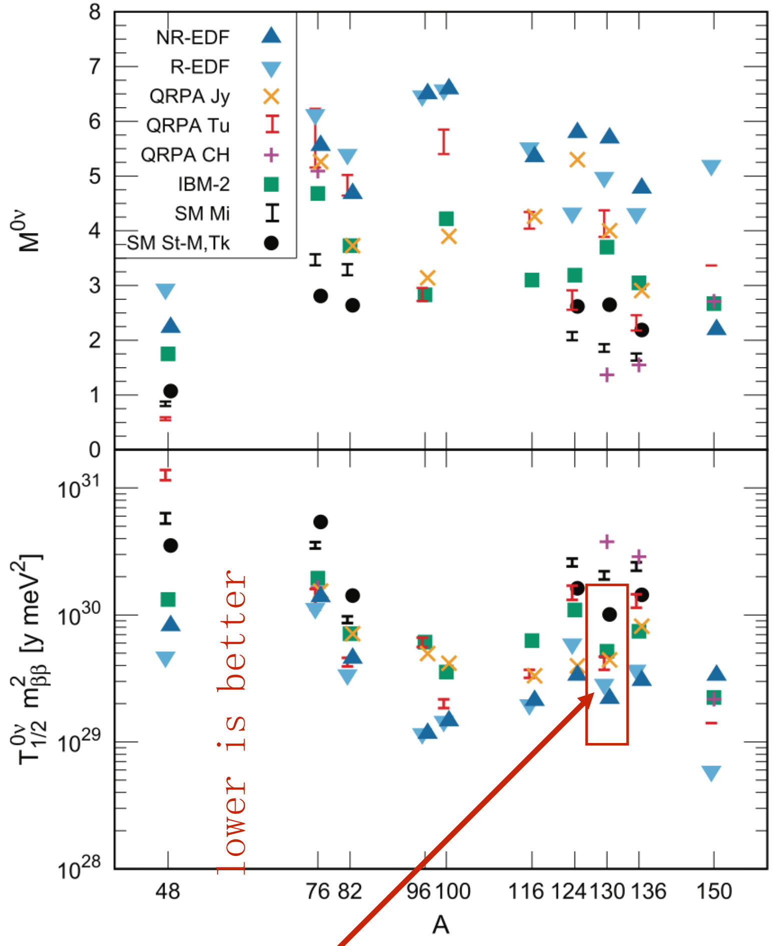
Tellurium for Double Beta Decay



^{130}Te & ^{136}Xe have the smallest $2\nu\beta\beta/0\nu\beta\beta$ ratio



Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301



Favourable $G_{0\nu}(Q,Z)\,|M_{0\nu}|^2$

Loaded Scintillator Approach to DBD

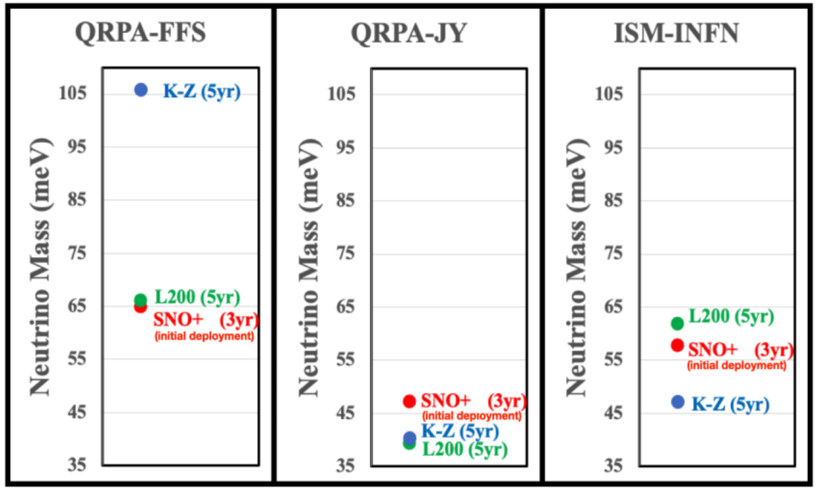
- Previous slide: "why tellurium?"
- This slide: "why in liquid scintillator?"

1. very low backgrounds: 2.9×10^{-4} counts/keV/$kg_{fiducial\ isotope}$/yr (GERDA is 5.2×10^{-4} ckky)
2. homogeneous detector volume – reliable background model
3. "target out" – ability to measure/constrain backgrounds *before* isotope added
4. "sideband analysis" – not just counts in a bin but distributions in position and energy verify detector response and background model
5. liquid detector permits: assays, chemistry; liquid medium can be modified *in situ* (e.g., adding more Te, more fluor)

A potential signal's dependence on the amount of isotope would be a strong confirmation!

SNO+ Te DBD Additional Considerations

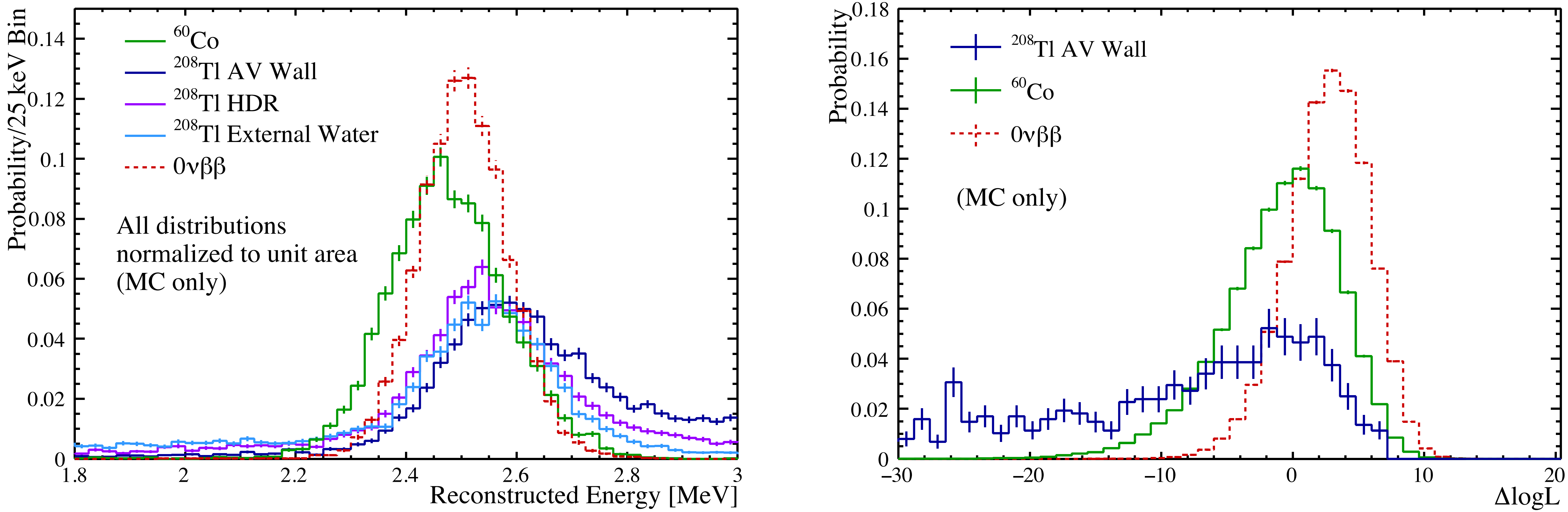
- ^{130}Te DBD is scalable, cost effective, unimpacted by challenges and cost of isotope enrichment
- KL-Z 800 has world-leading sensitivity (upper limit 36-156 meV) and highlights the strength of the loaded LS DBD approach
- Complementarity of isotope
  - NME model dependencies → importance of complementary isotopes and approaches
  - purification of Te underground is novel technology
  - "target out" analysis is a strong and unique feature; all non-Te backgrounds constrained prior to adding any Te



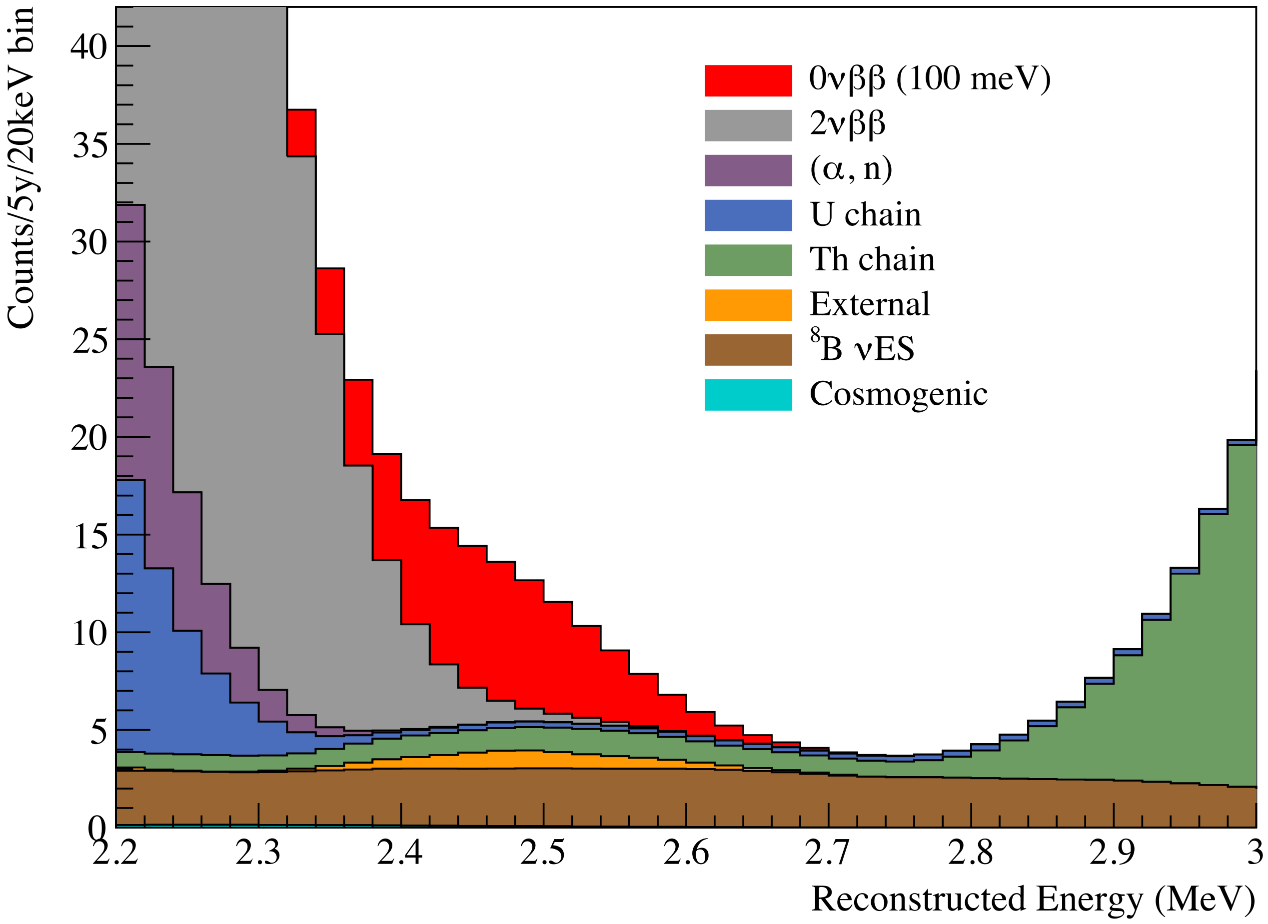
- SNO+ also has single-site/multi-site background constraining power

Dunger and Biller, *NIM A*, 943, 162420, 2019)

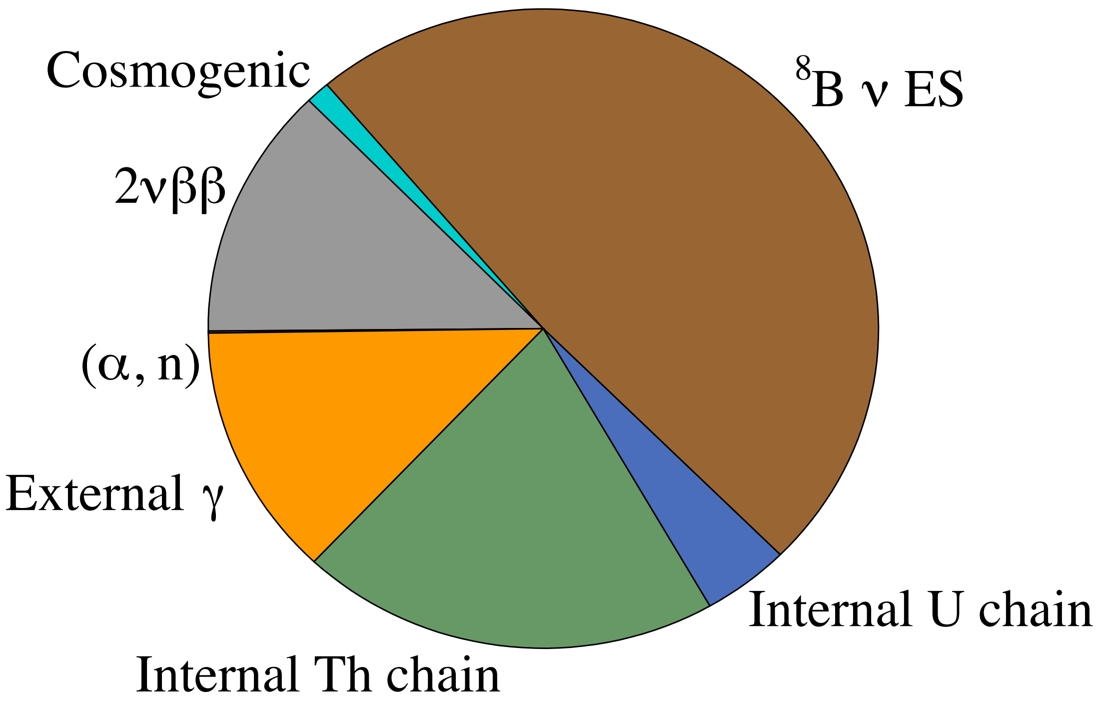
SNO+ Multi-site Background Likelihood Constraint



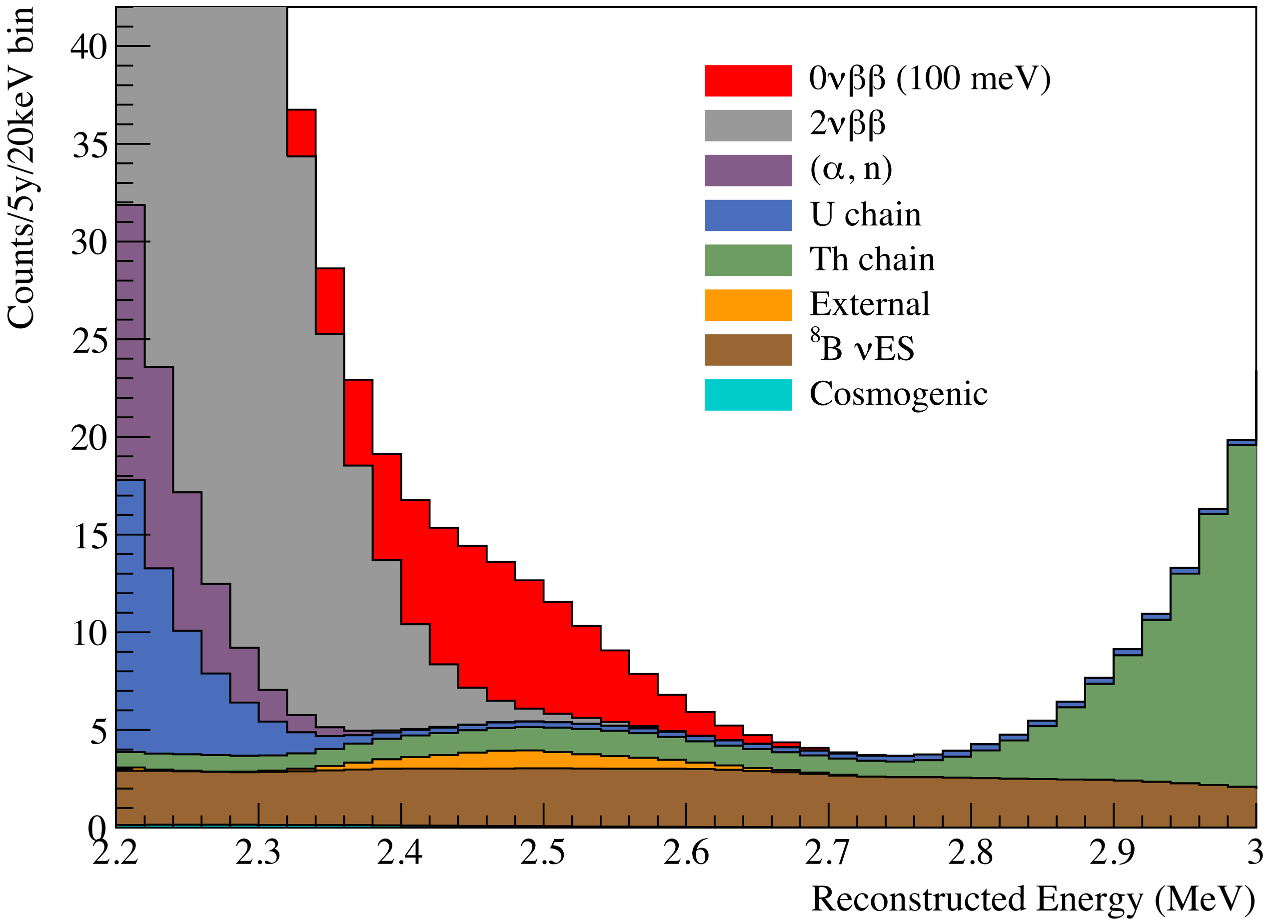
DBD Spectrum and Backgrounds Pie Chart



ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

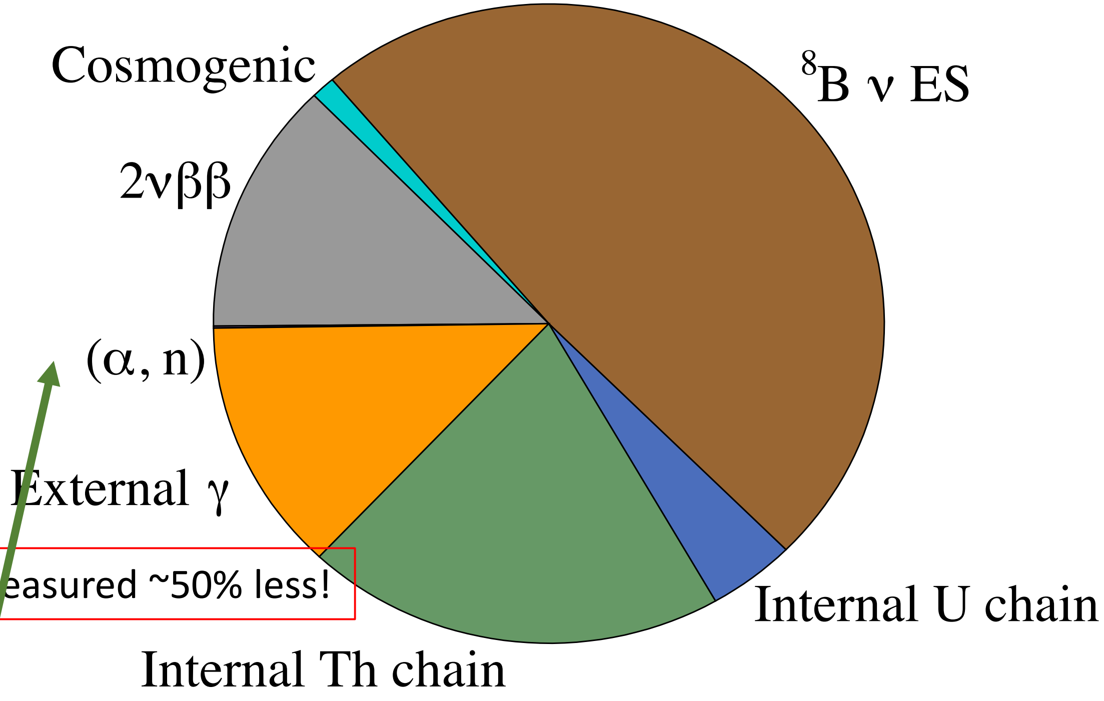


DBD Spectrum and Backgrounds Pie Chart



ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

known

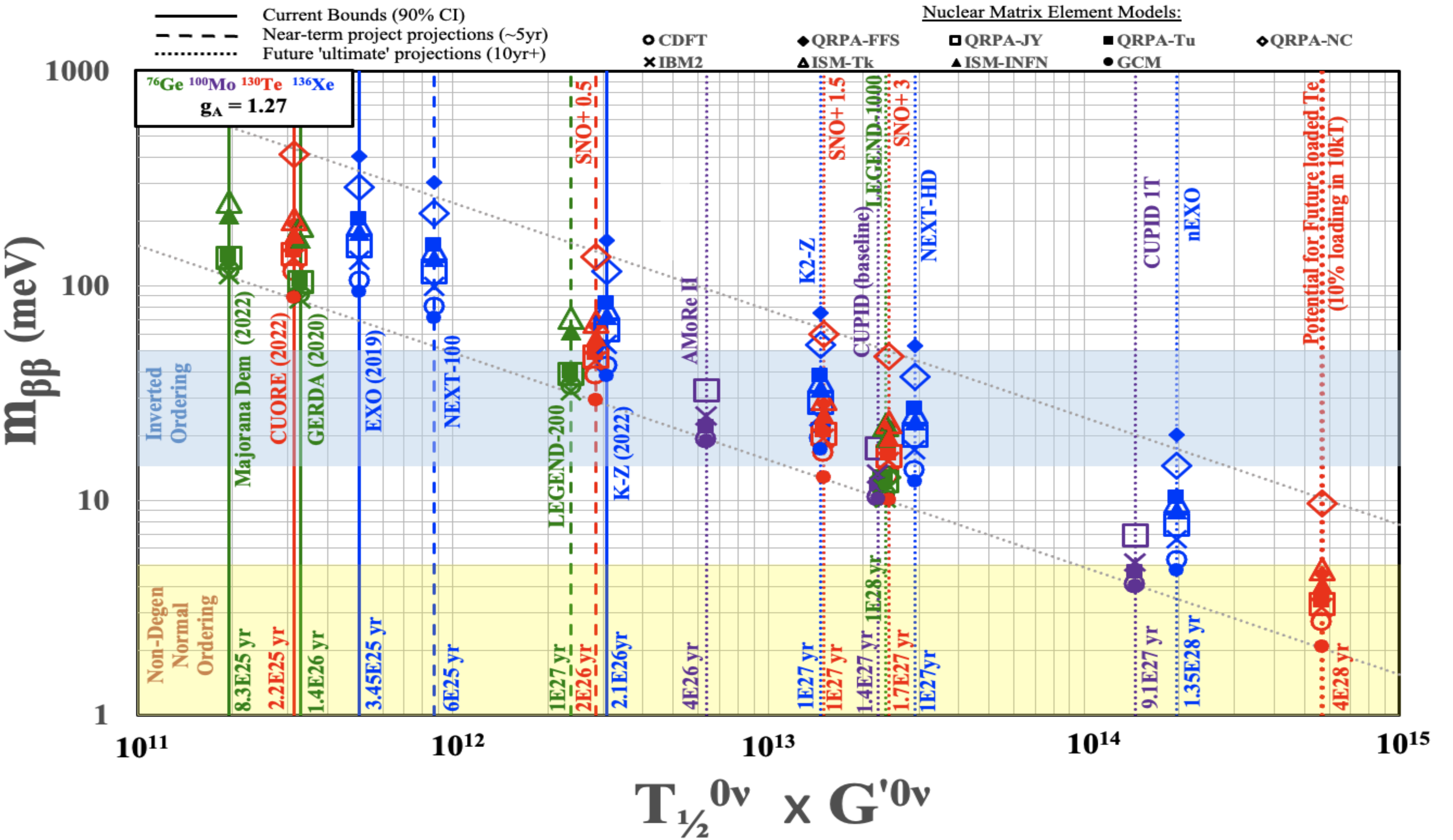


measured ~50% less!

higher than model but still negligible

background levels U/Th in LS (few 10^{-17} g/g) meets DBD requirement (sub-dominant to Te)

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



Status of SNO+ Te DBD

Tellurium systems are built and ready for operation!

Full-scale test (200 kg batch) of telluric acid purification is being prepared and will start next month

Target date: mid-2025 for Te loading in the SNO+ detector

Telluric acid purification

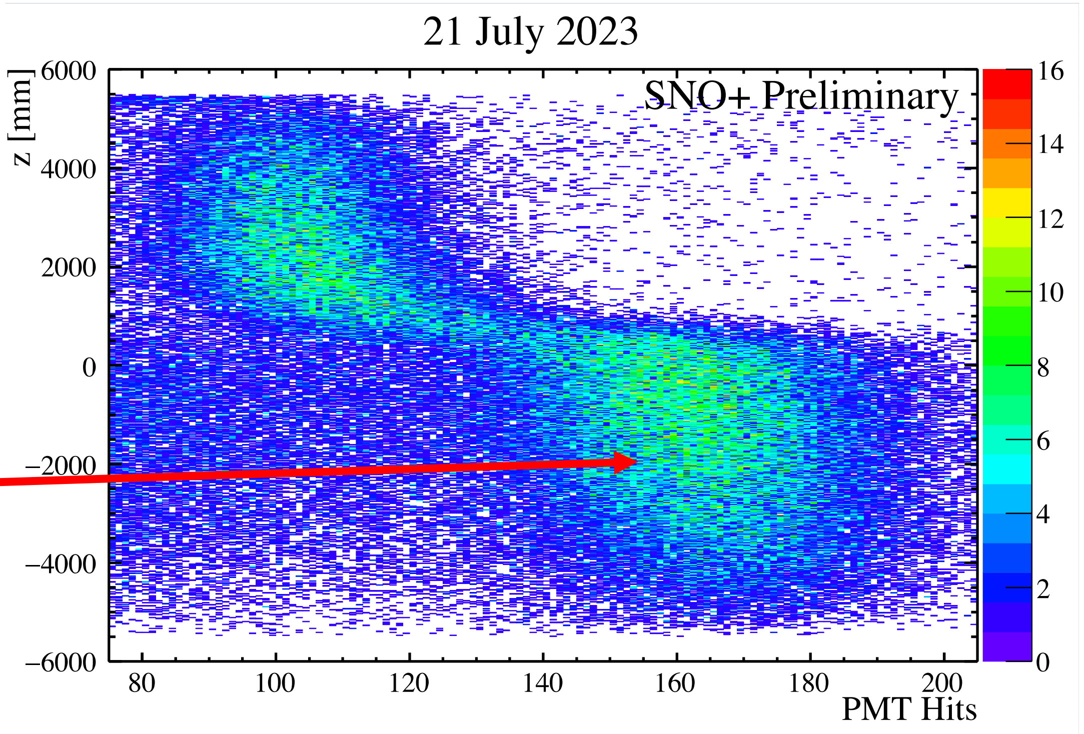
Te-diol synthesis

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



Summary

- SNO+ is an operating liquid scintillator neutrino detector filled with LAB + 2.2 g/L PPO and taking data
- Diverse program of neutrino physics is underway
- Already-built underground tellurium plants represent novel technology in the field of low-radioactivity techniques and are beginning full-scale, test batch operations in the next few months
- Operating the plants and demonstrating their capabilities is the next step towards preparing to load SNO+ with Te for the $0\nu\beta\beta$ phase (aiming for 0.5%→1.5% loading, to begin in 2025)


SNO+ 2023