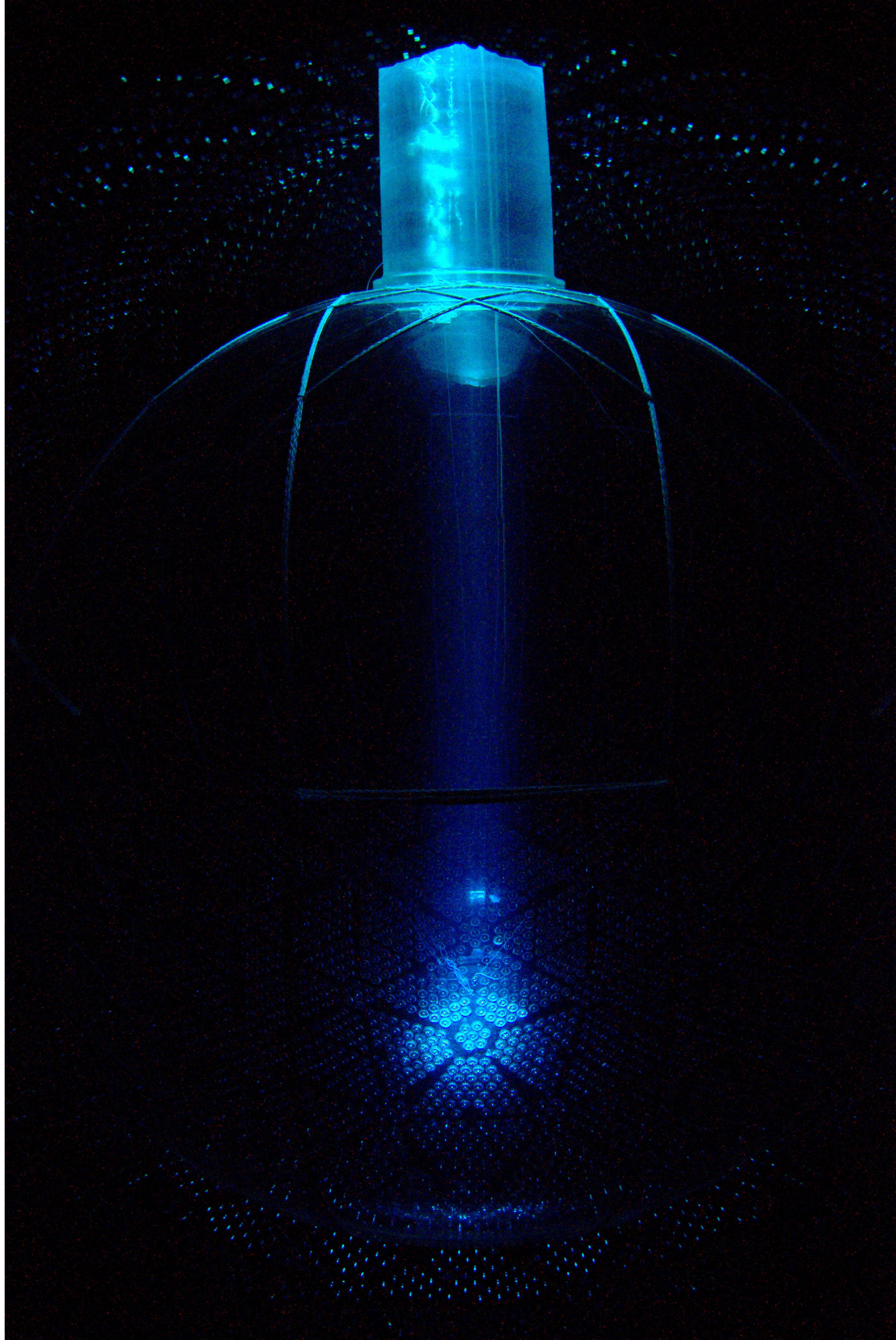
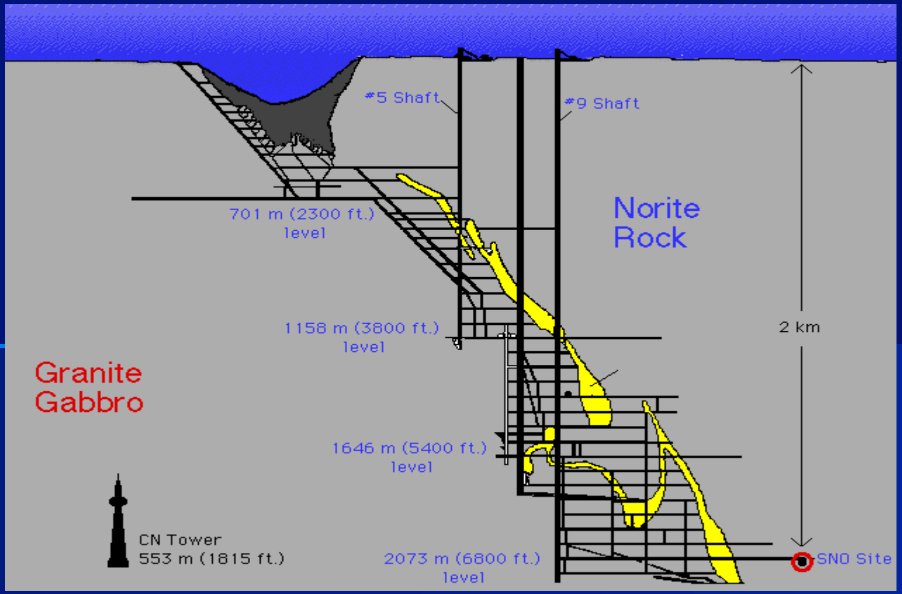
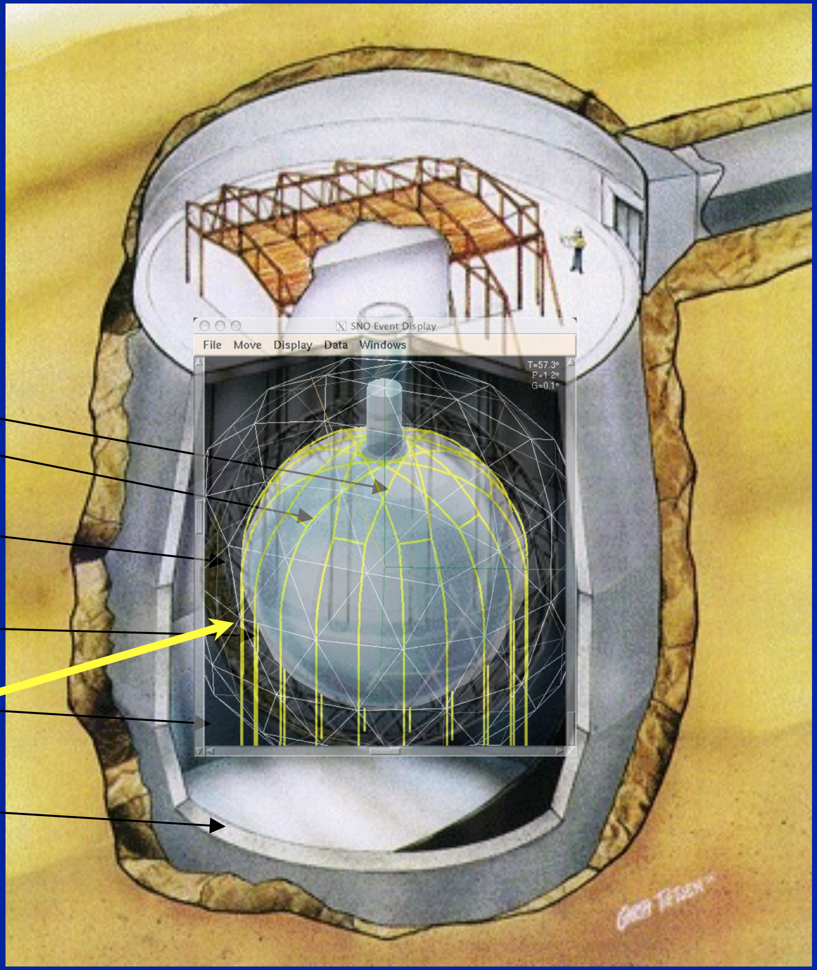
Mark Chen

Queen’s University and CIFAR

May 26, 2023







~~1000 tonnes D_2O~~ → **780 tonnes liquid scintillator**

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~50% photocathode coverage)

1700 tonnes inner shielding H_2O

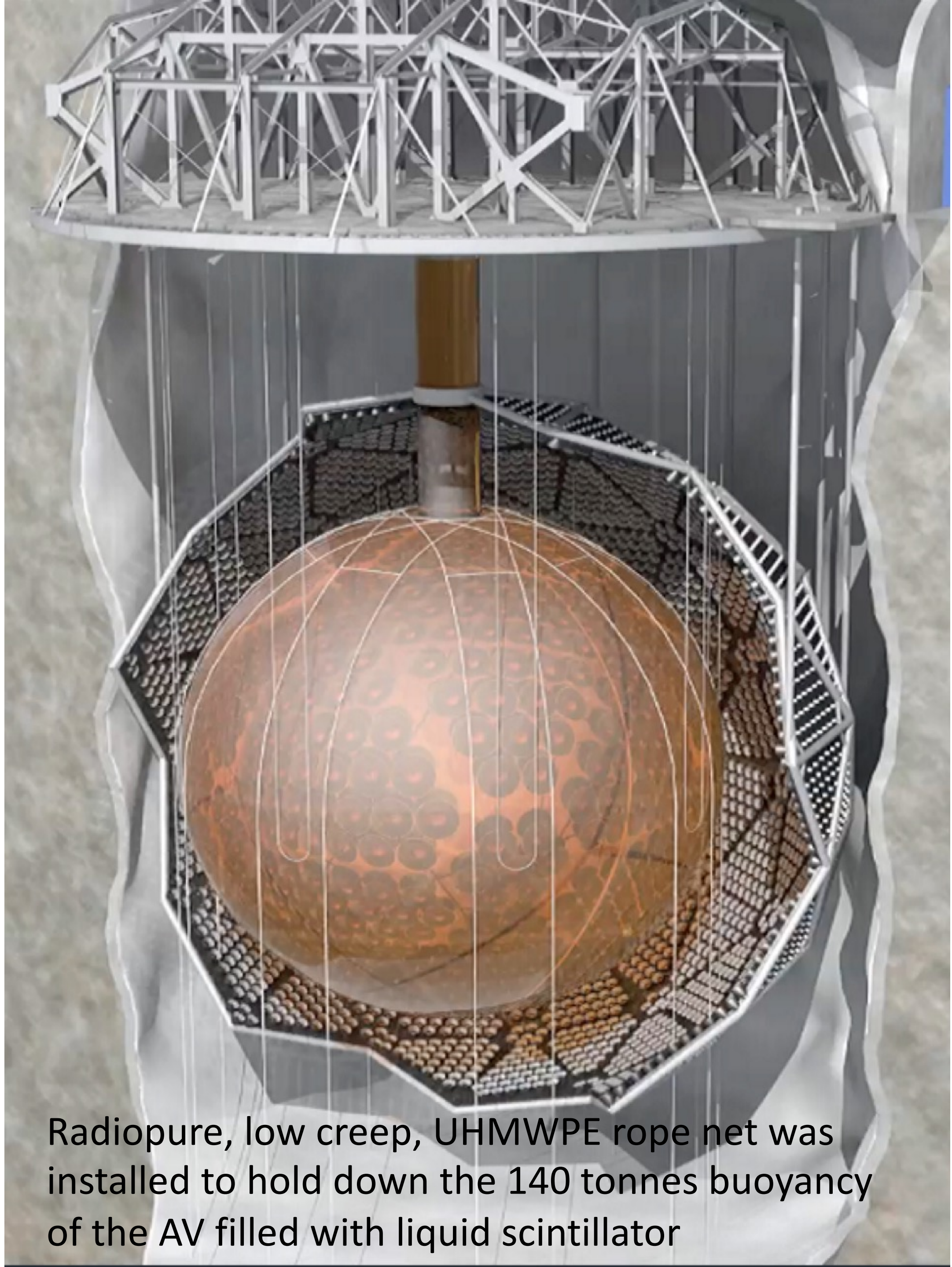
5300 tonnes outer shielding H_2O

Urylon liner radon barrier

hold-down rope net

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

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

Restorations

SNO was a classic, but even classics need some restorations…

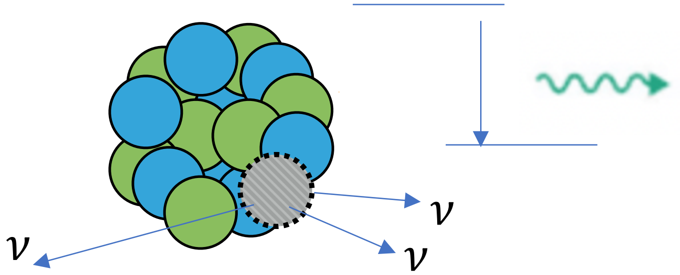
- SNO Cavity floor liner had been badly torn at the end of SNO; had to be remade (during SNO+ hold-down anchor installation)
- Anchor plate installation involved *drilling* into concrete and rock *inside an ultra-low background neutrino detector*
- Submersible pump that drained the SNO AV had self-destructed, 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 this, would SNO+ still have low backgrounds?

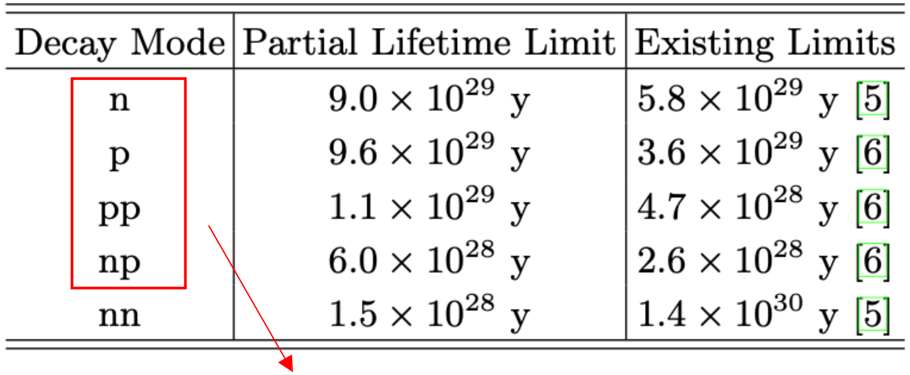
SNO+ Water Phase

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*

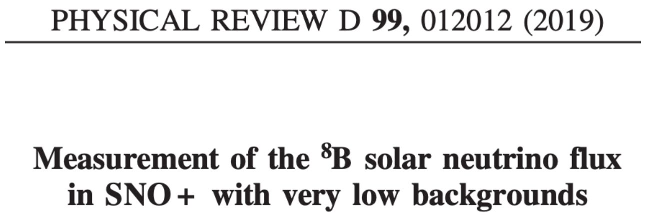


Decay Mode	Partial Lifetime Limit	Existing Limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

world-leading limits set by SNO+

- Solar neutrinos
  - detected via neutrino-electron elastic scattering

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



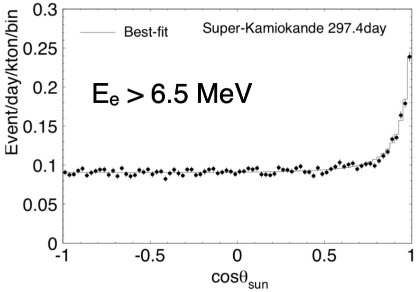
PHYSICAL REVIEW D **99**, 012012 (2019)

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

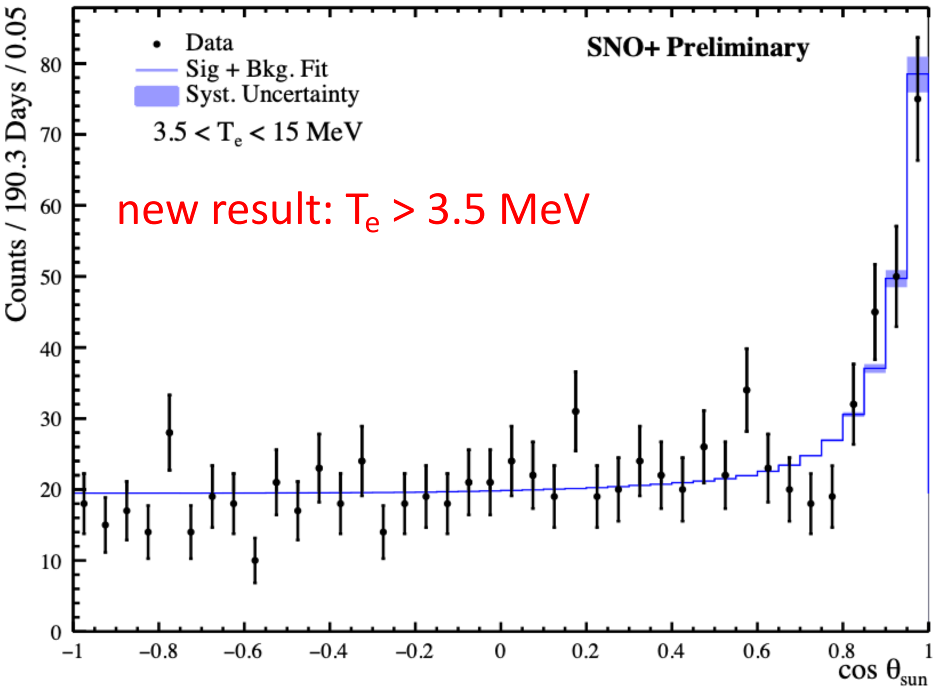
  - now with *even lower backgrounds*

- First observation of reactor $\bar{\nu}_e + p \rightarrow e^+ + n$ events using *pure* water (undoped)
  - published in *Phys. Rev. Lett.* on March 1, 2023
  - made possible by ~50% neutron detection efficiency (highest in a water Cherenkov detector)

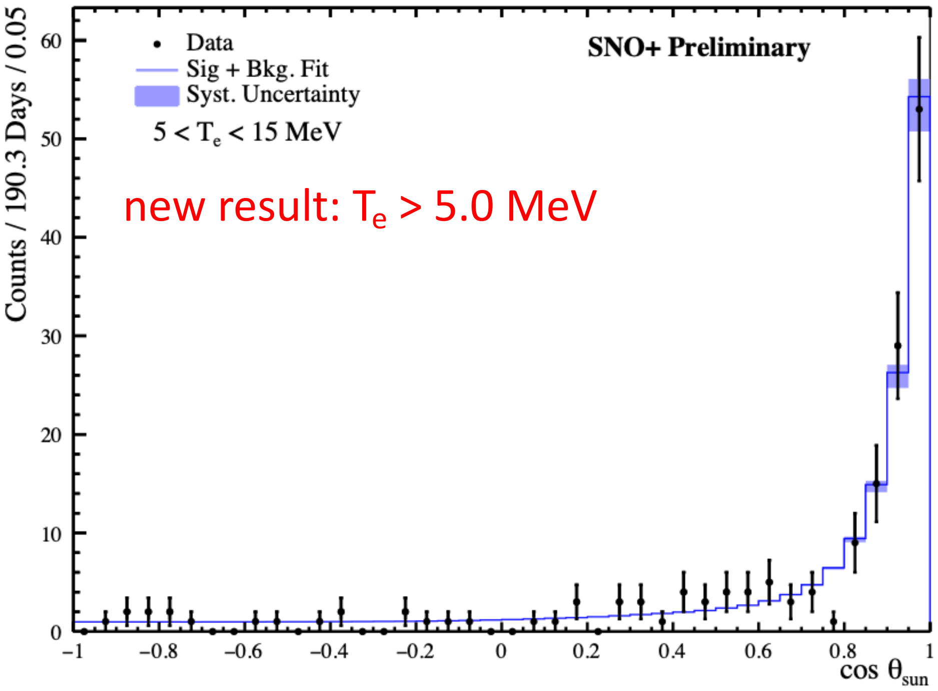
^{8}B solar neutrinos in SNO+ Water Phase



first Super-K result, for comparison

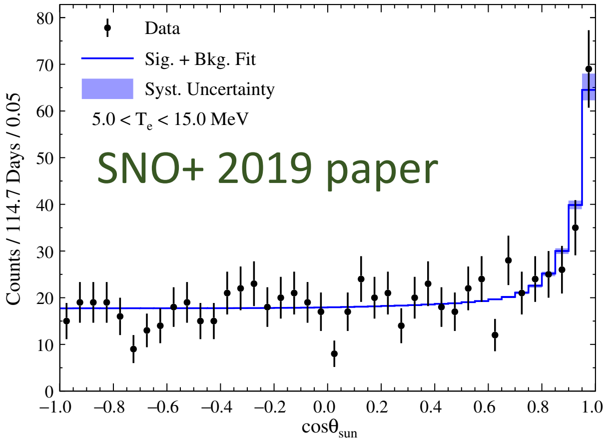


new result: $T_e > 3.5$ MeV



new result: $T_e > 5.0$ MeV

same 5.0 MeV threshold



SNO+ 2019 paper

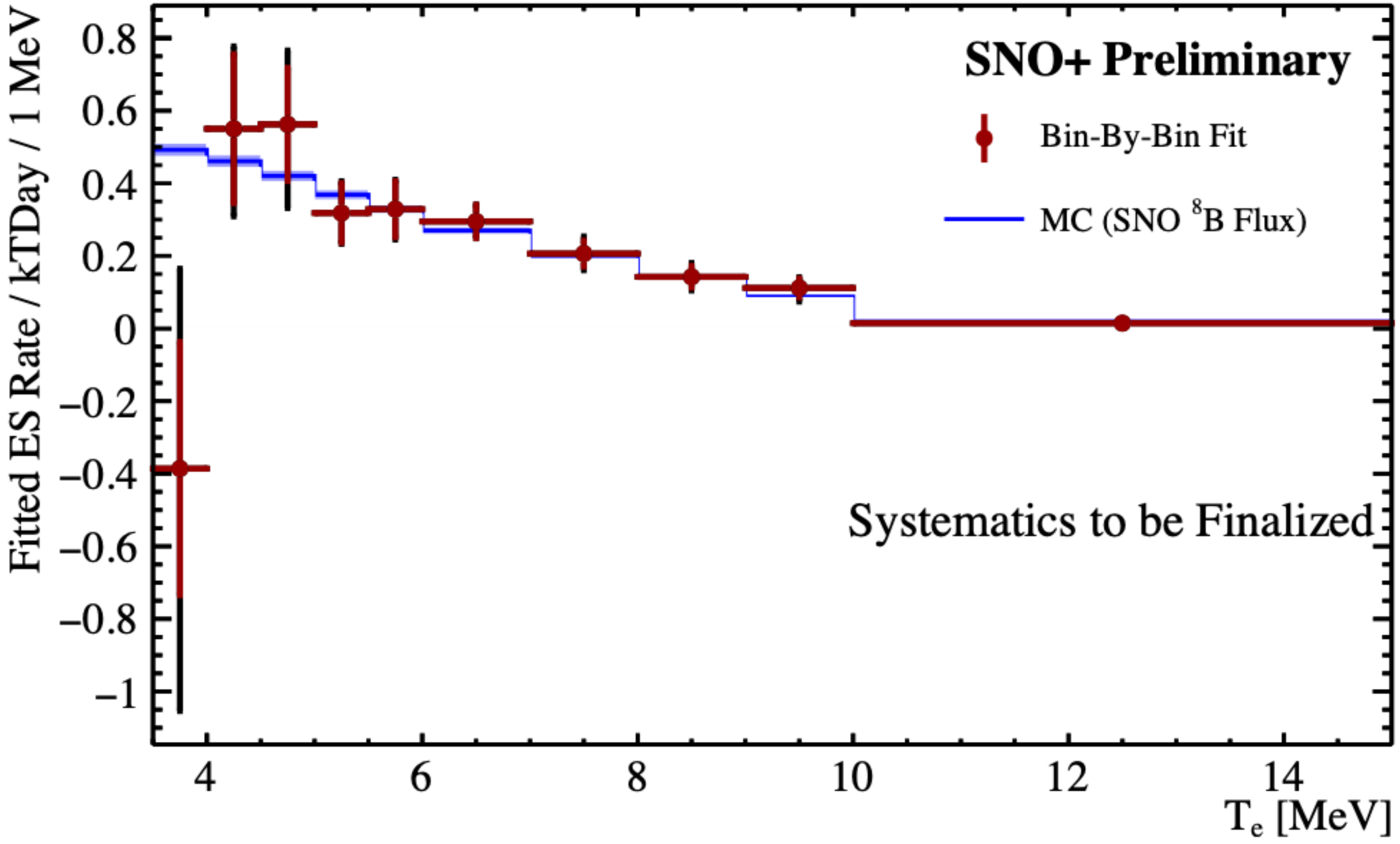
Our latest results with data from the extended water phase, with ~1/10 Rn levels (new SNO+ cover gas system)

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

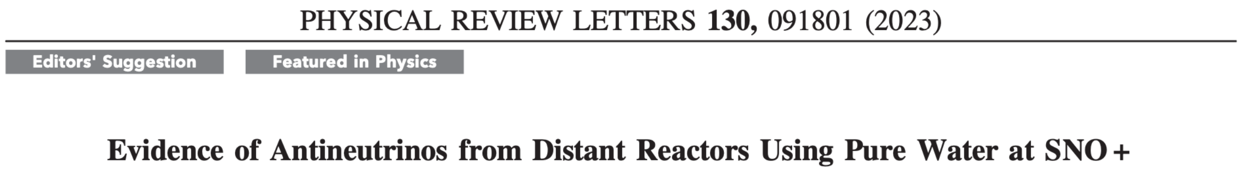
result as shown at Neutrino 2022



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

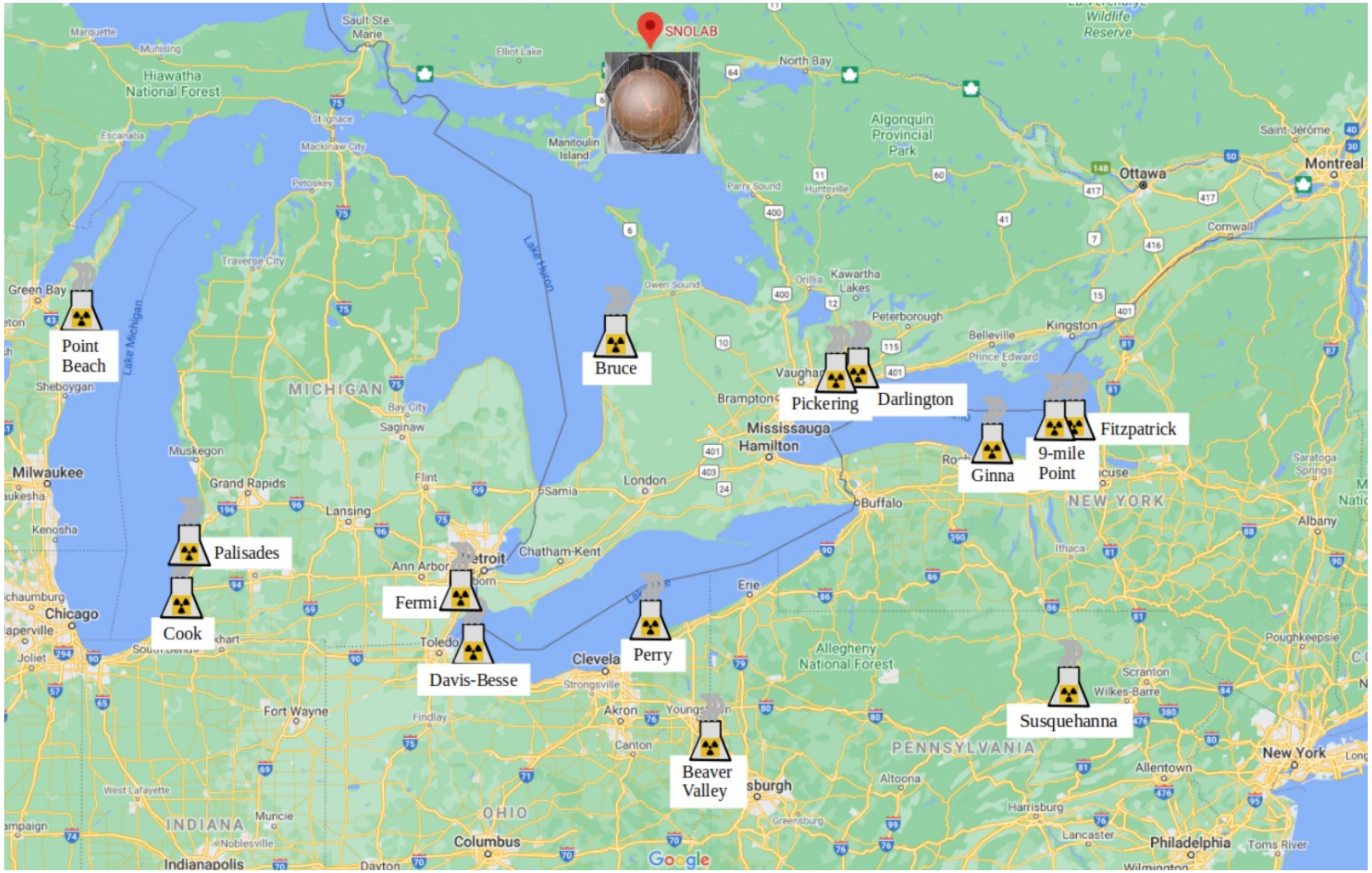
Featured in Physics

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

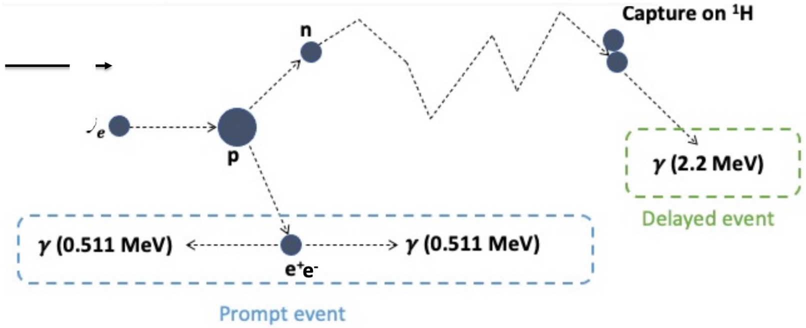
technical papers

- 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)



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

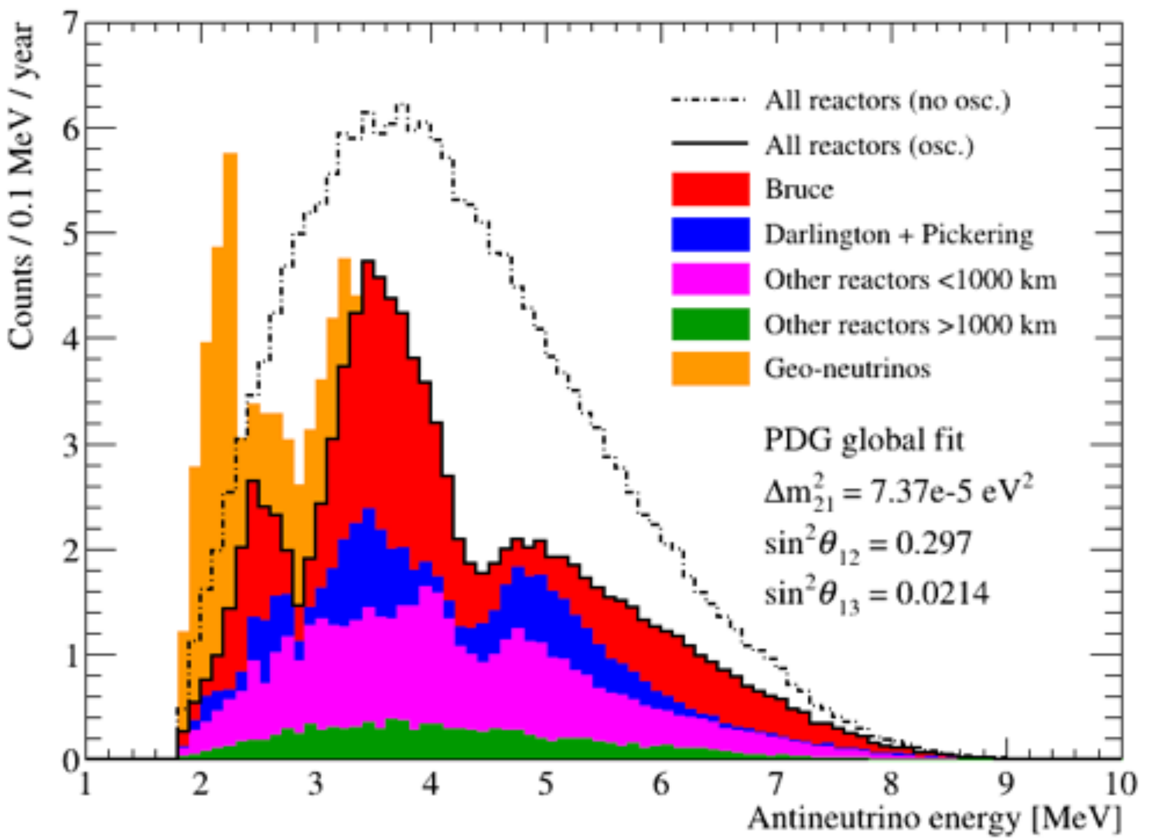
Coincidence event

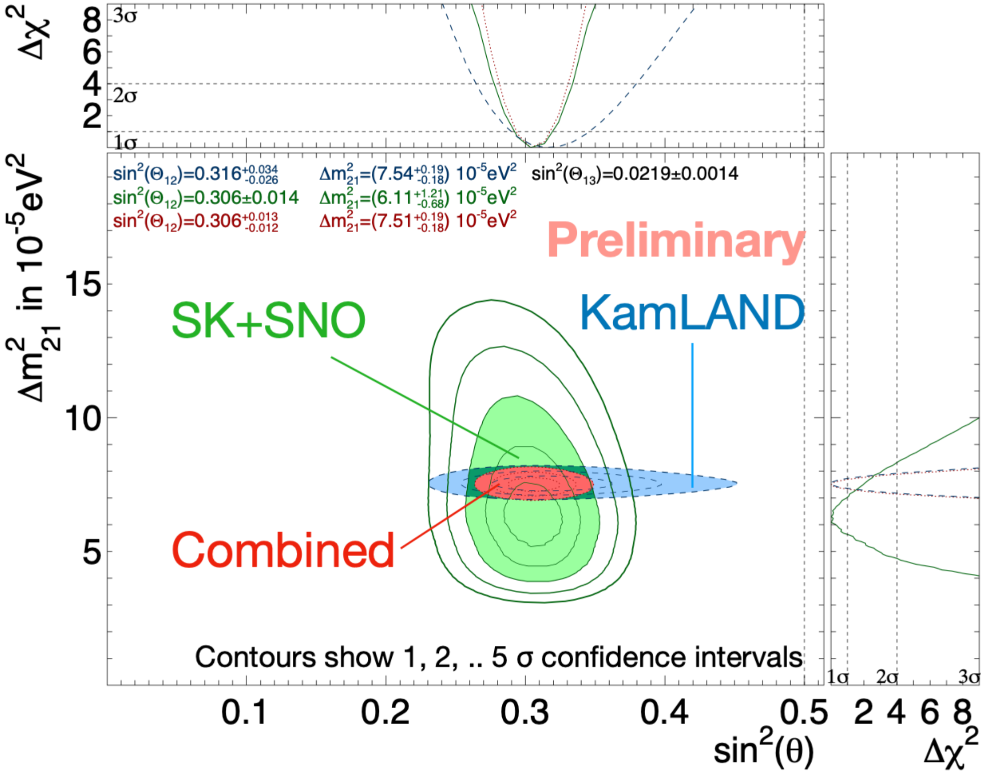
Prompt – positron kinetic energy (several MeV)
plus 1.022 MeV from annihilation γ's

Delayed – neutron capture 2.2 MeV γ

Antineutrinos in SNO+ Scintillator

Scintillator Phase – Reactor antineutrino oscillations Δm^2_{12} (plus geo neutrinos) are one of the main science goals of the Scintillator Phase

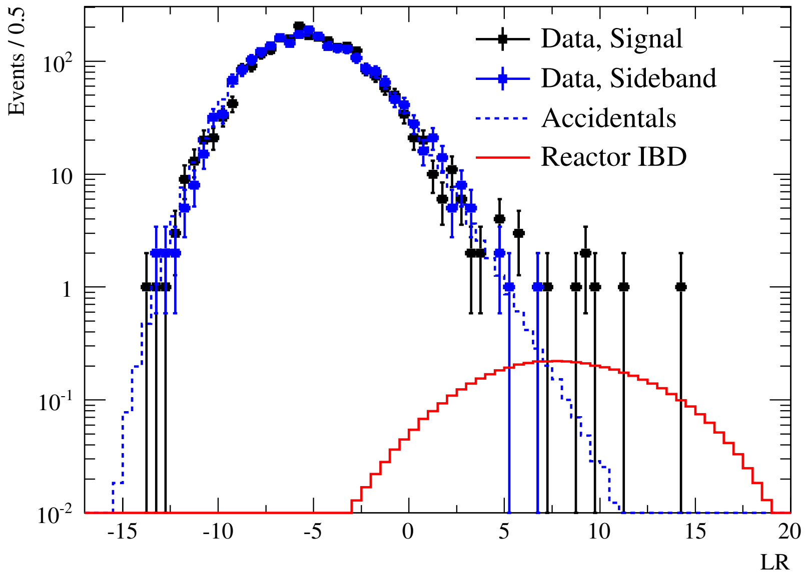


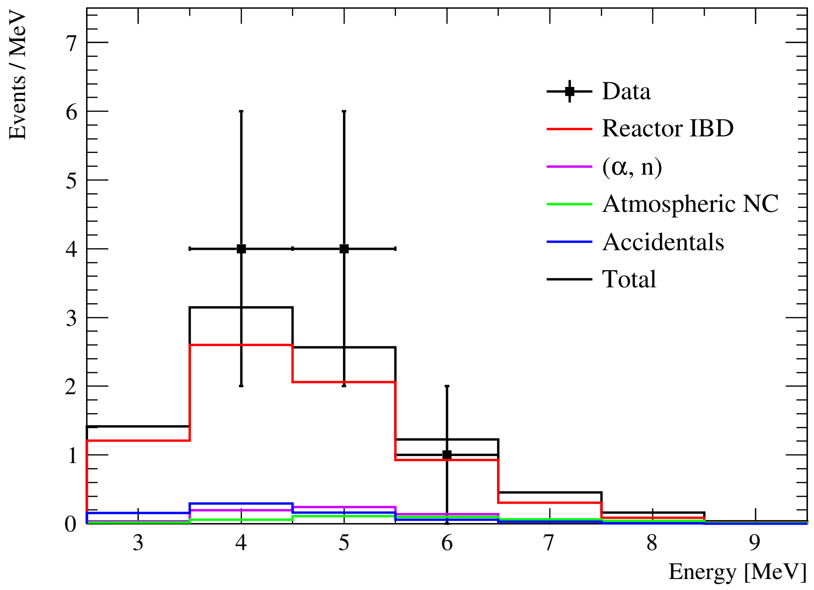


Antineutrinos in SNO+ Water? Yes!

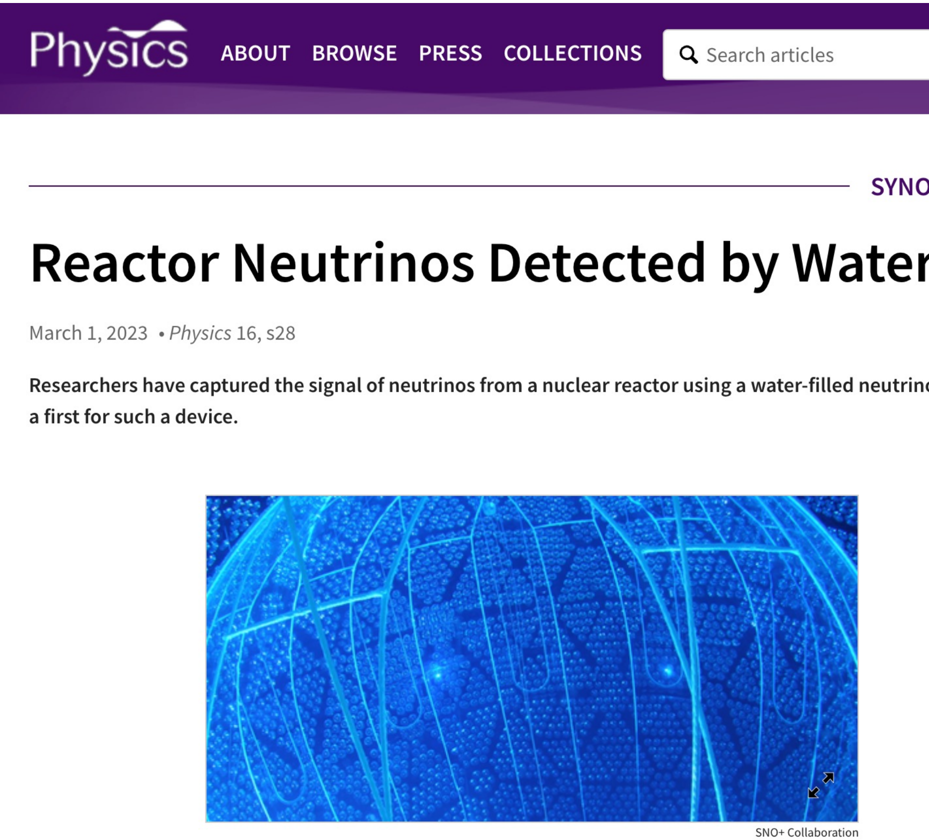
Water Phase – Detection of IBD events (reactor antineutrinos) using pure water → this is a first

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





Science Press



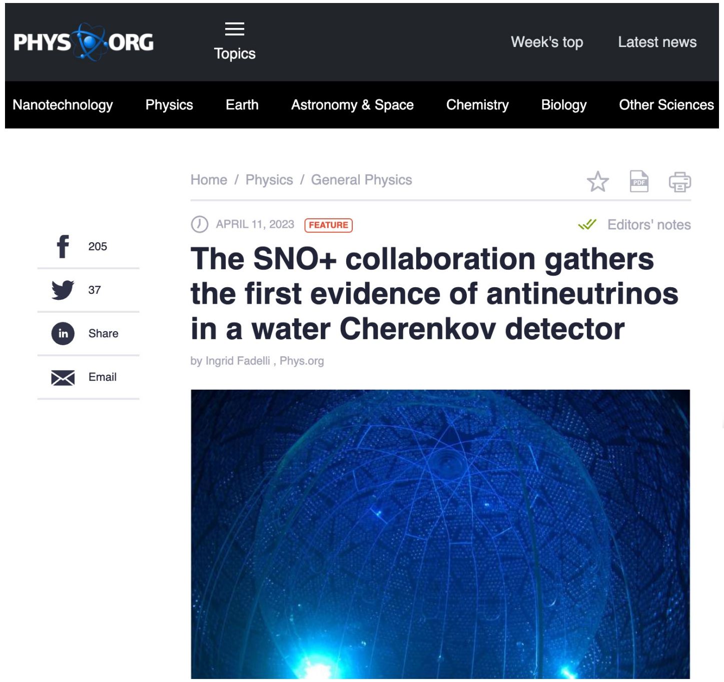
SYNOPSIS

Reactor Neutrinos Detected by Water

March 1, 2023 • *Physics* 16, s28

Researchers have captured the signal of neutrinos from a nuclear reactor using a water-filled neutrino detector, a first for such a device.

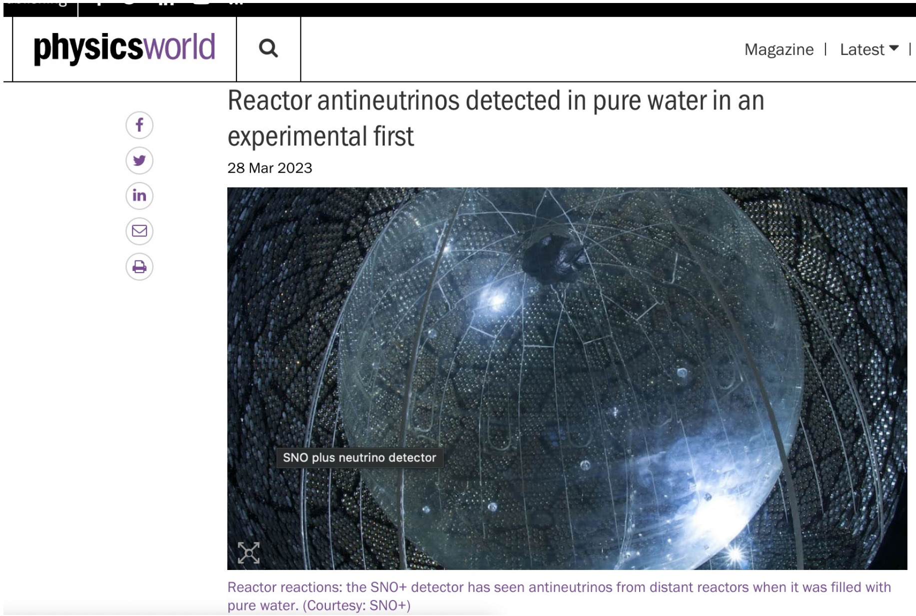
SNO+ Collaboration



APRIL 11, 2023 FEATURE Editors' notes

The SNO+ collaboration gathers the first evidence of antineutrinos in a water Cherenkov detector

by Ingrid Fadelli , Phys.org



Reactor antineutrinos detected in pure water in an experimental first

28 Mar 2023

Reactor reactions: the SNO+ detector has seen antineutrinos from distant reactors when it was filled with pure water. (Courtesy: SNO+)

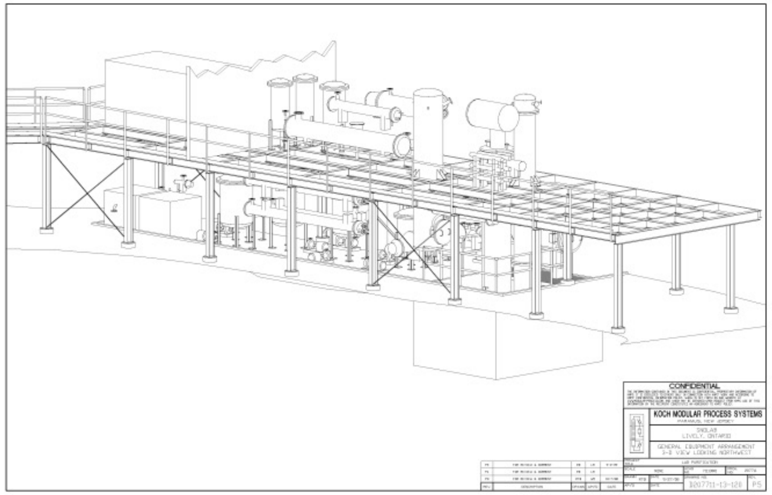
SNO+ Scintillator Purification Plant

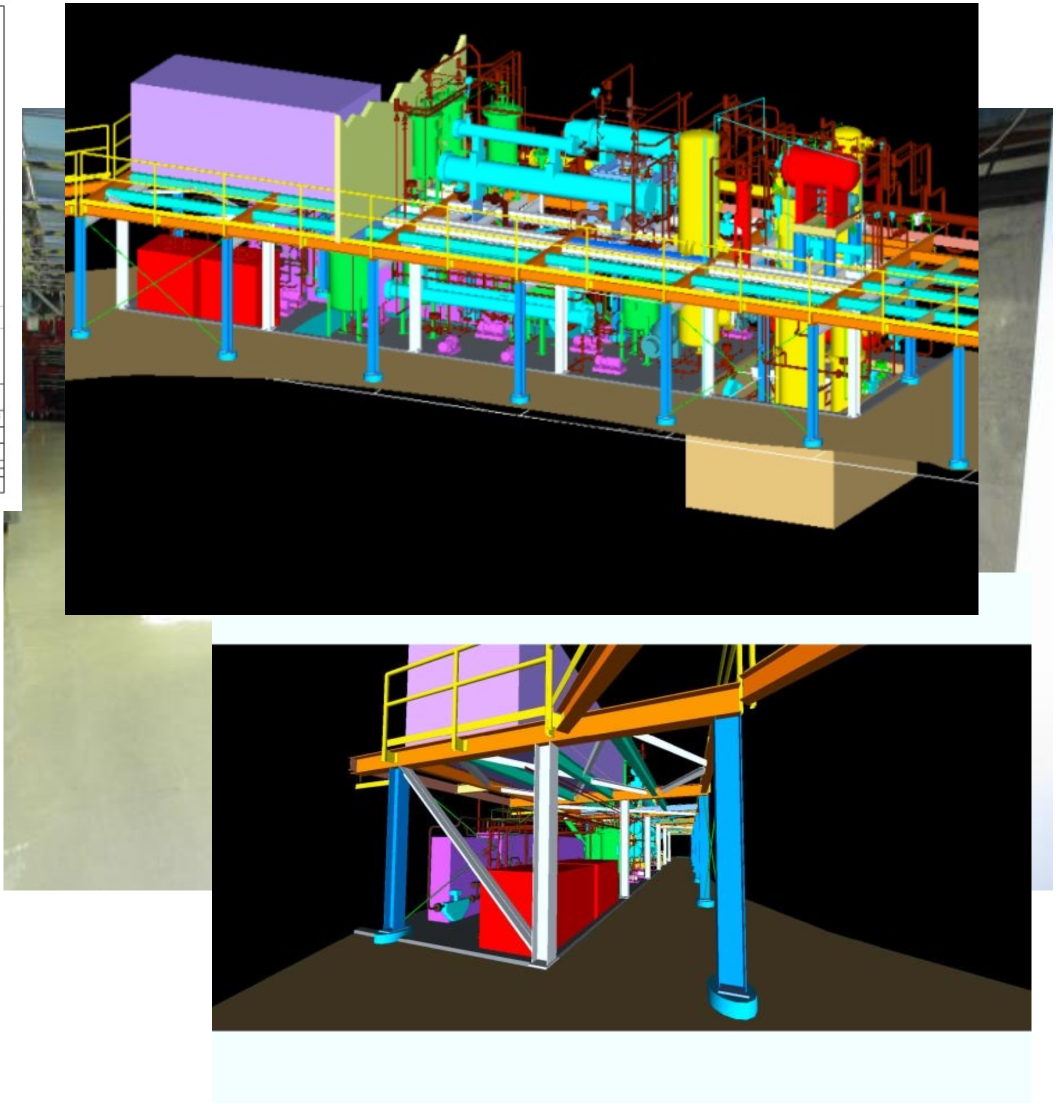
- reinforced mezzanine steel
- made D2O pit deeper “mining in a clean room”
- installed columns, vessels, heat exchangers, tank, pumps, valves, high-grade sanitary piping (orbital-welded, electropolished stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)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

the SNO heavy water purification system was here

SNO+ Scintillator Purification Plant

- rein
- mac
  in a
- inst
  hea
  pun
  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






SCINTILLATOR
SCINTILLATOR 1042
E-101
V-101
E-3

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

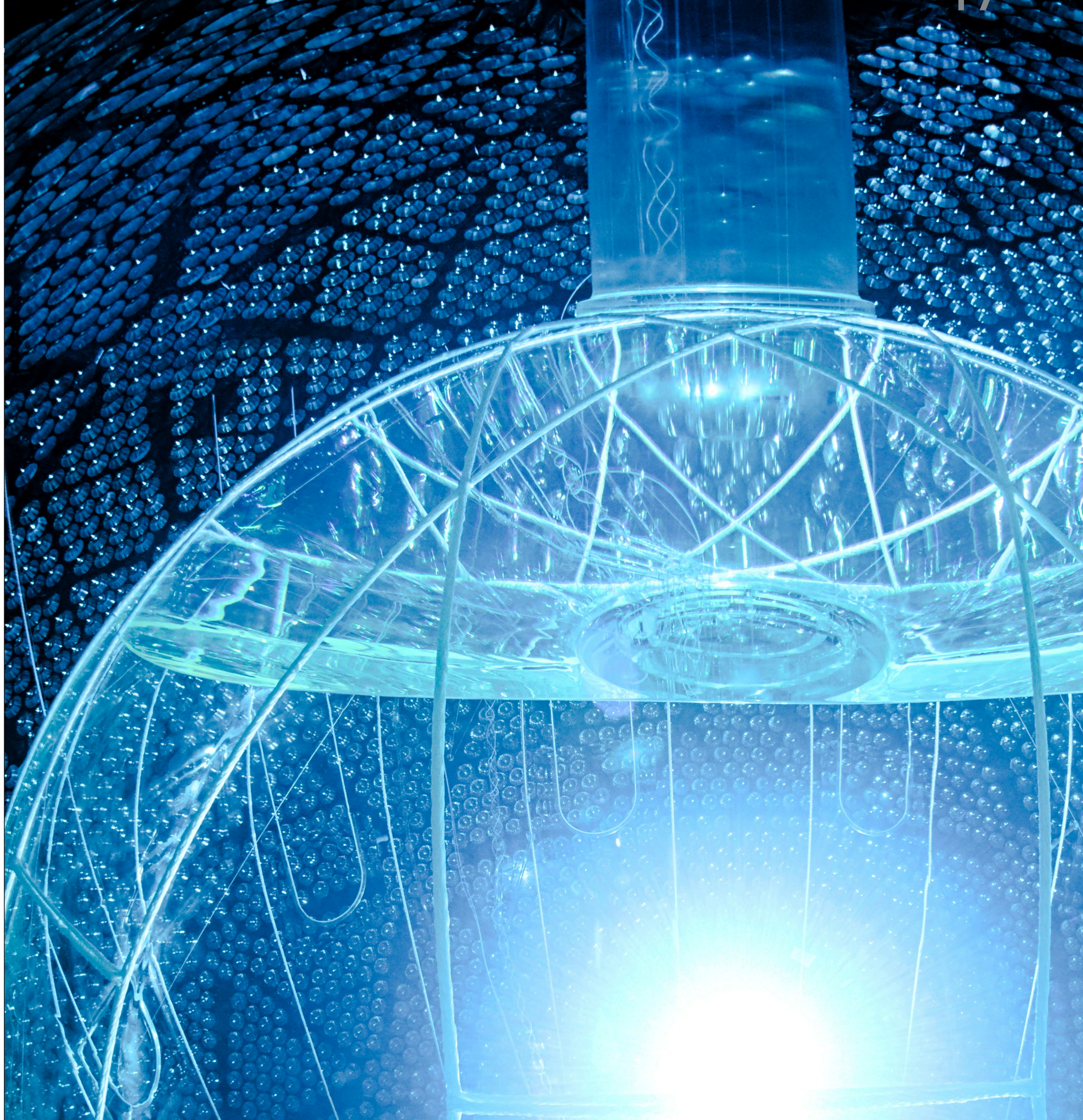
$(4.7\pm1.2)\times10^{-17}\ g_{U}/g_{LAB}$

^{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)

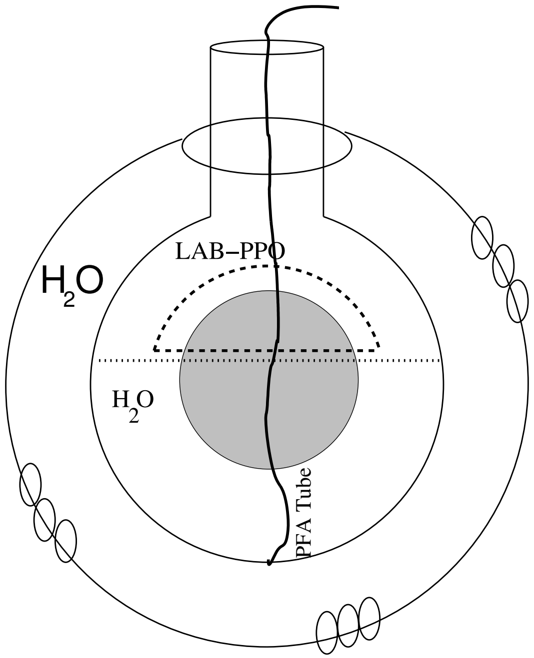
- Optical properties of LS 👍
- Also physics from SNO+ partial fill…

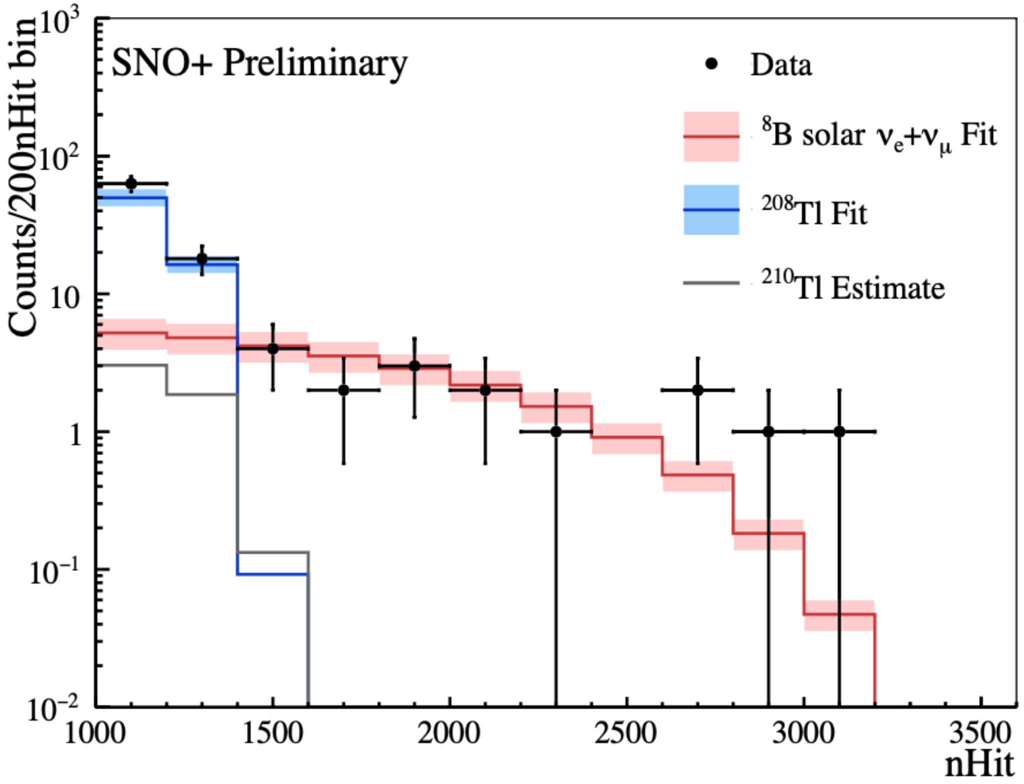


Partial-fill data taken in 2020

Physics with Partial-Fill Scintillator

- ^{8}B solar neutrinos in partial-fill scintillator
  - demonstrates SNO+ LS solar neutrino detection, even in a sub-optimal detector configuration

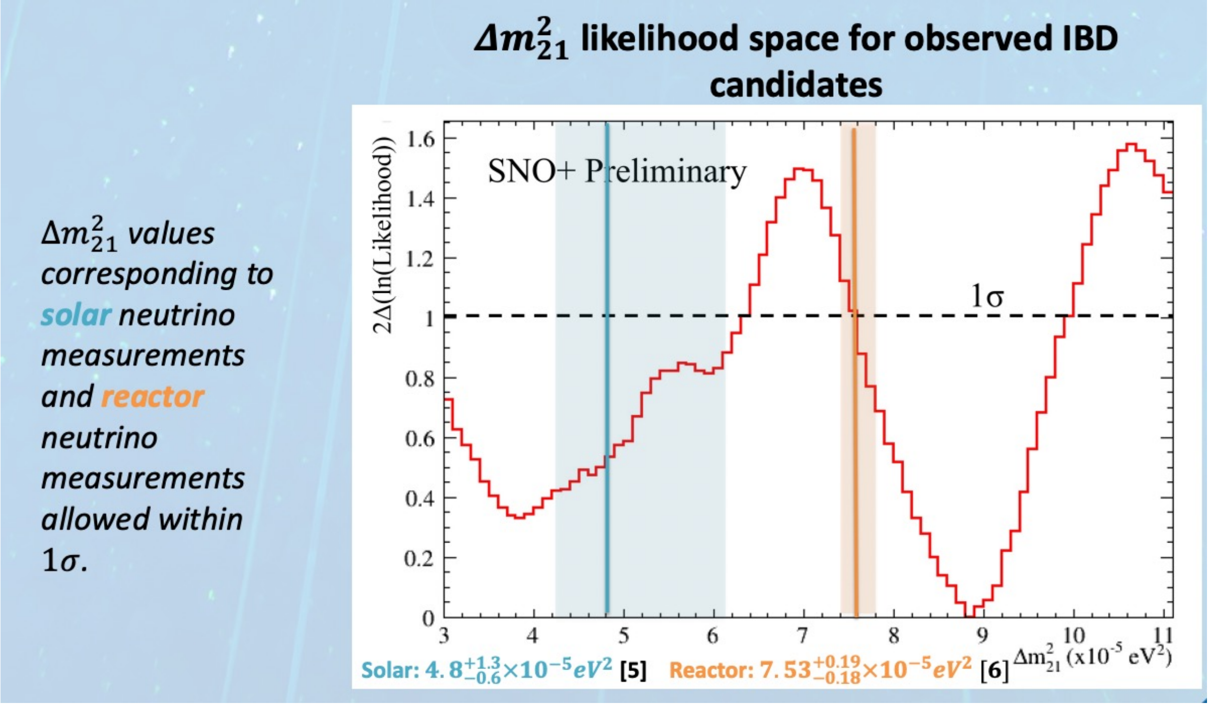




Partial-fill data taken in 2020

SNO+ reactor antineutrinos in partial-fill

- Publication in preparation; the result won’t challenge our understanding of Δm^2_{12}; but draws attention to upcoming SNO+ measurements with full LS that will



Δm^2_{21} likelihood space for observed IBD candidates

*Δm^2_{21} values corresponding to **solar** neutrino measurements and **reactor** neutrino measurements allowed within 1σ.*

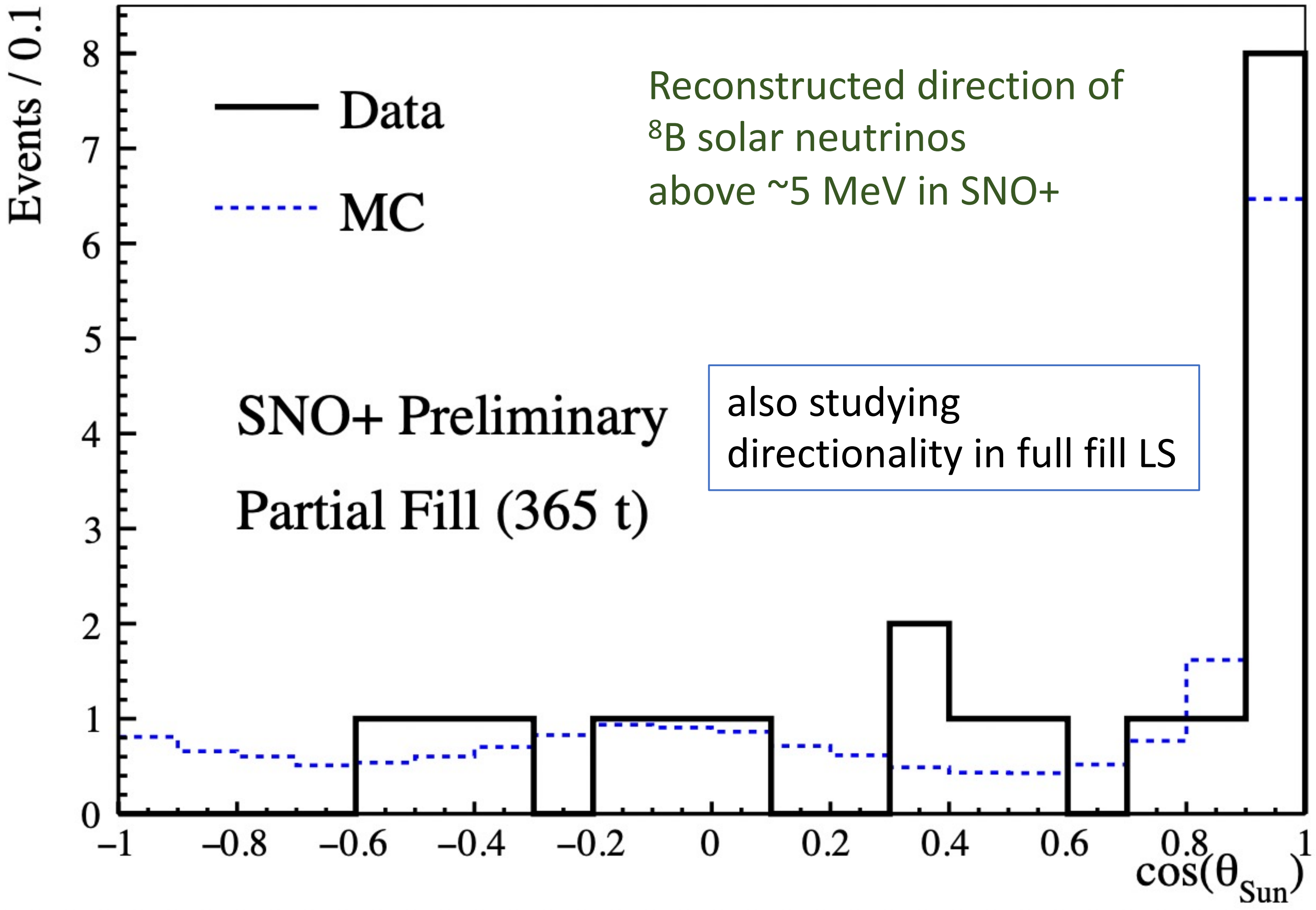
Solar: $4.8^{+1.3}_{-0.6}\times10^{-5}eV^2$ [5] Reactor: $7.53^{+0.19}_{-0.18}\times10^{-5}eV^2$ [6]

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
- new 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!

Publication being prepared



Reconstructed direction of ^{8}B solar neutrinos above ~5 MeV in SNO+

also studying directionality in full fill LS

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 lots of 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!

1 year ago, scintillator operations concluded and we started the…

SNO+ Scintillator Phase

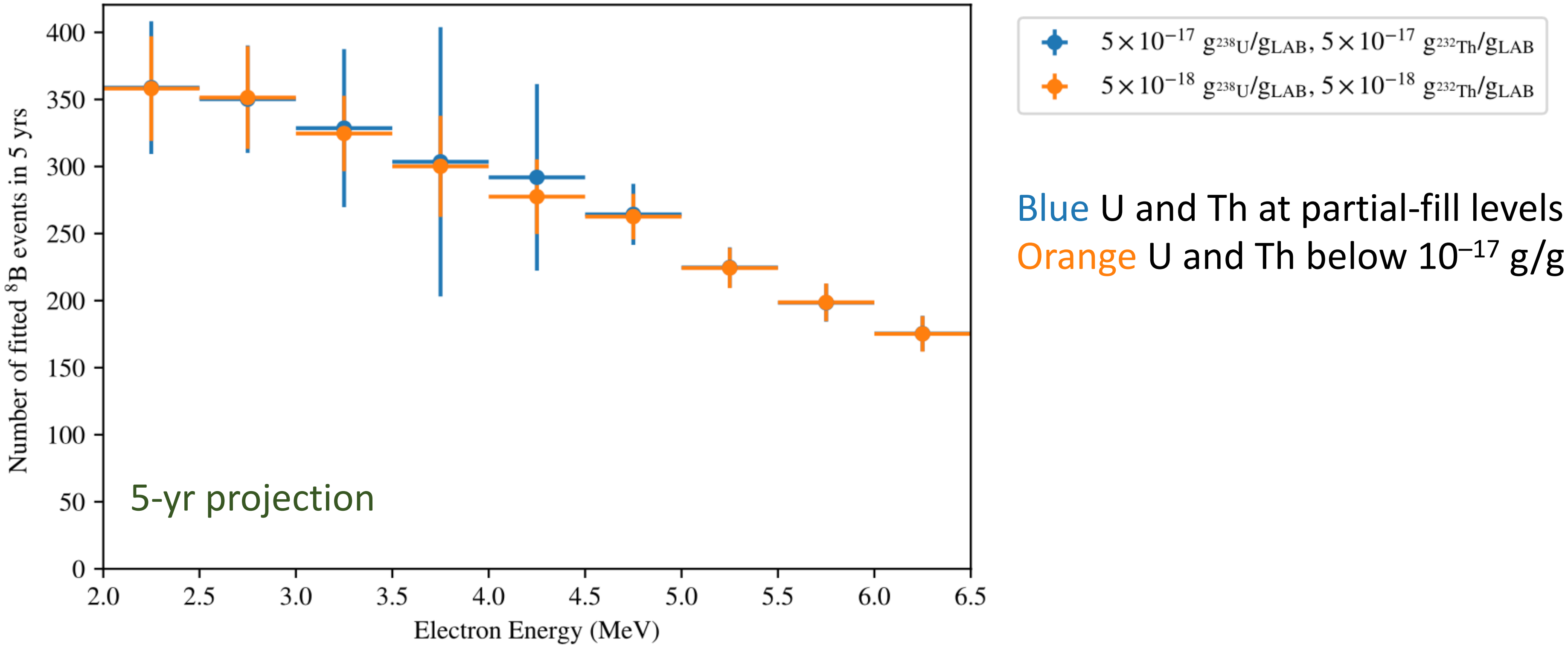
Physics Goals in the Scintillator Phase

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

Objectives for SNO+ Scintillator Phase (Full):

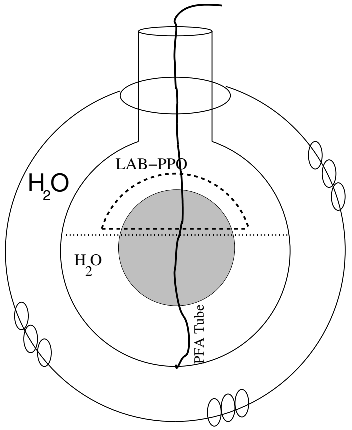
^{8}B Solar Neutrinos at Low Energies

- See if we can measure below 3 MeV (hasn't been done before)
  - larger fiducial volume than Borexino
  - cosmogenic backgrounds much lower than KamLAND (e.g., no ^{10}C, ^{11}C)



5-yr projection

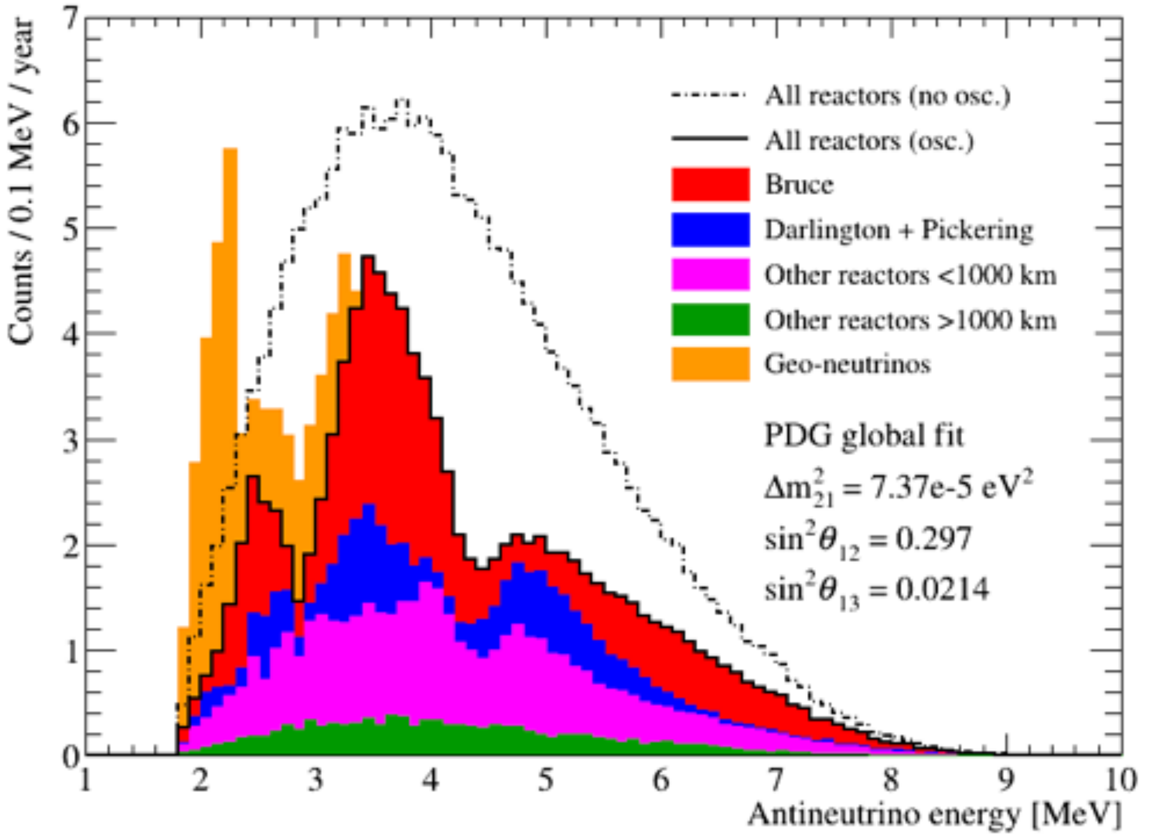
Blue U and Th at partial-fill levels
Orange U and Th below 10^{-17} g/g

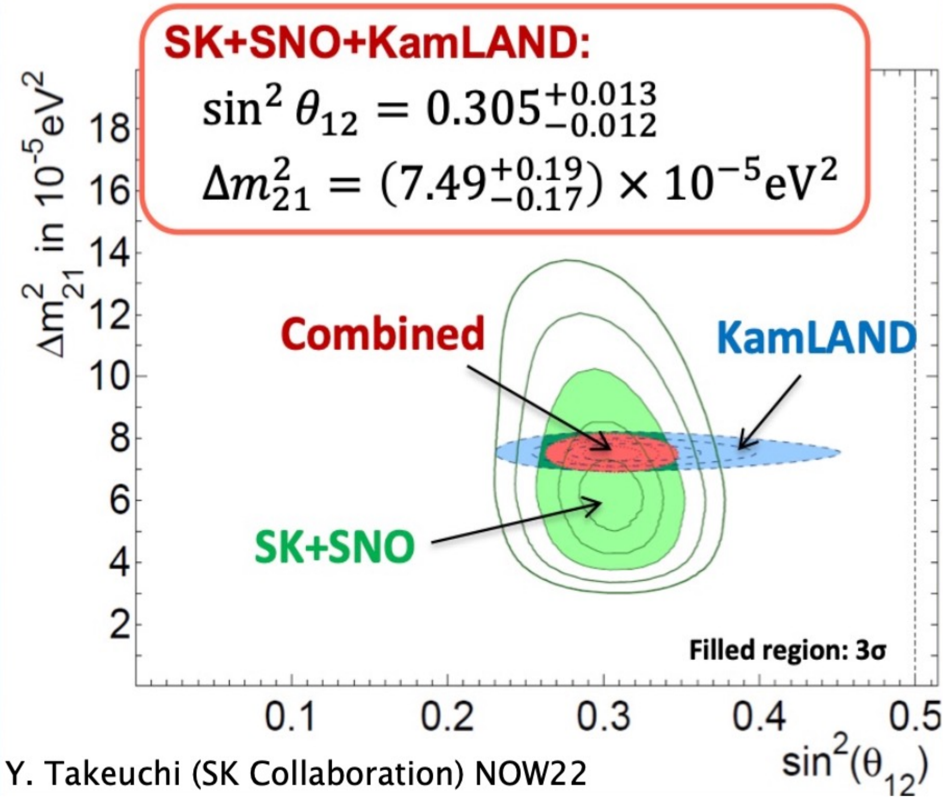


Reminder: partial-fill was sub-optimal configuration

Antineutrinos in SNO+ Scintillator

Scintillator Phase – Reactor antineutrino oscillations Δm_{12}^2 (plus geo neutrinos) are one of the main science goals

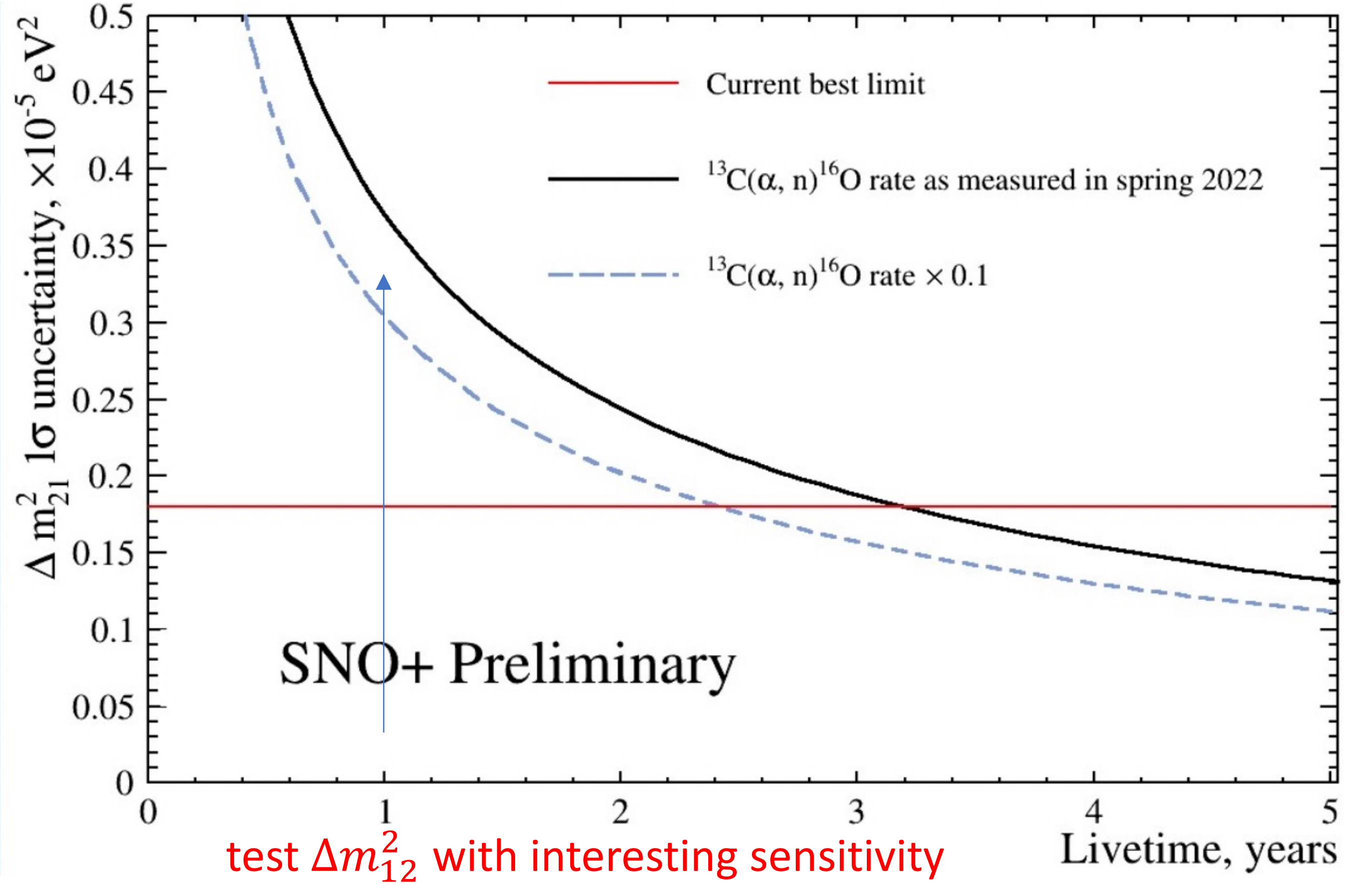




Y. Takeuchi (SK Collaboration) NOW22

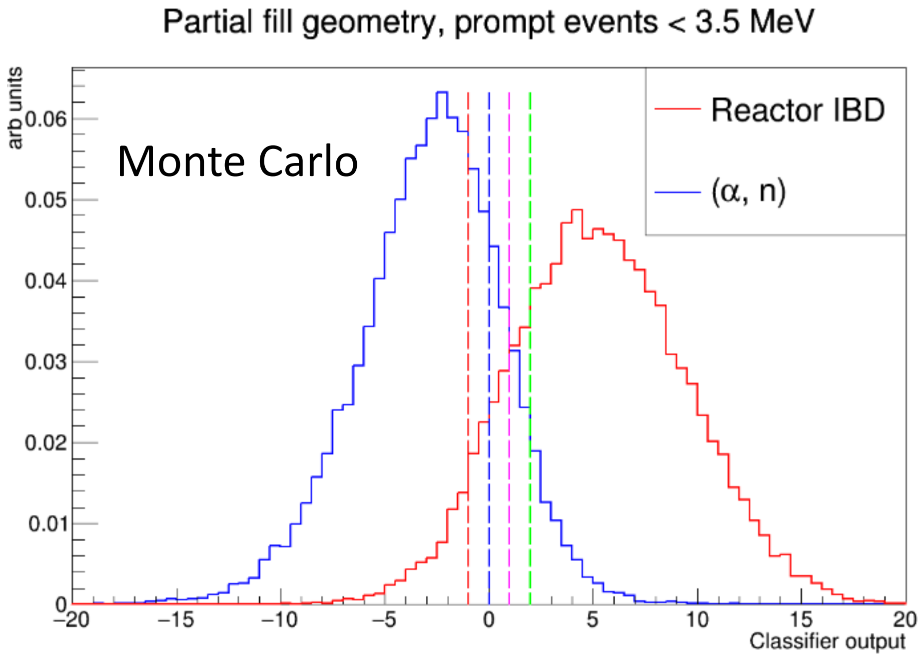
physics motivation for reactor neutrino oscillation studies

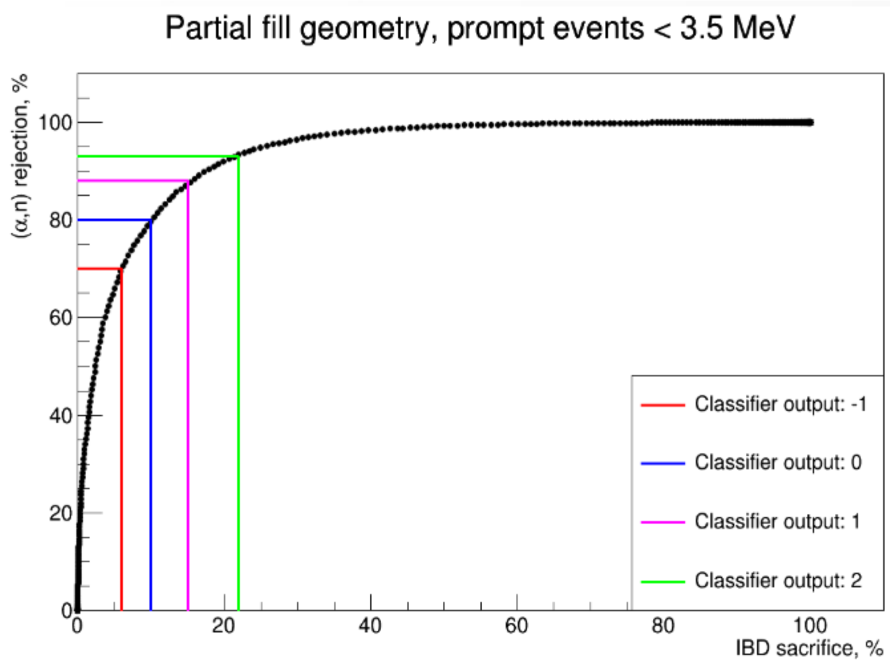
Objectives for SNO+ Scintillator Phase:
Reactor Antineutrinos Δm_{12}^2

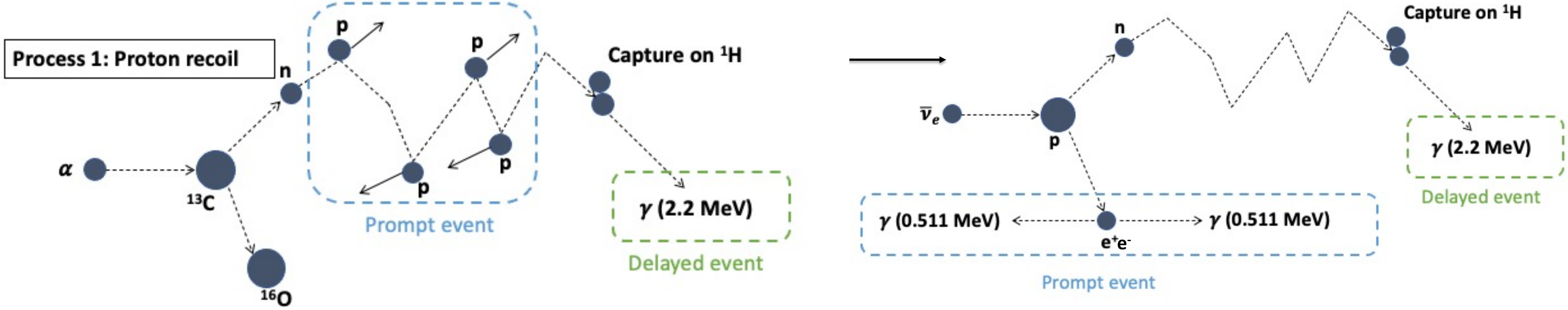


test Δm_{12}^2 with interesting sensitivity already after 1 year (shape is more important than rate) to distinguish 5.1 from 7.5 ($\times 10^{-5}$ eV^2)

(α,n) Classifier (tested in partial-fill) – new SNO+ development

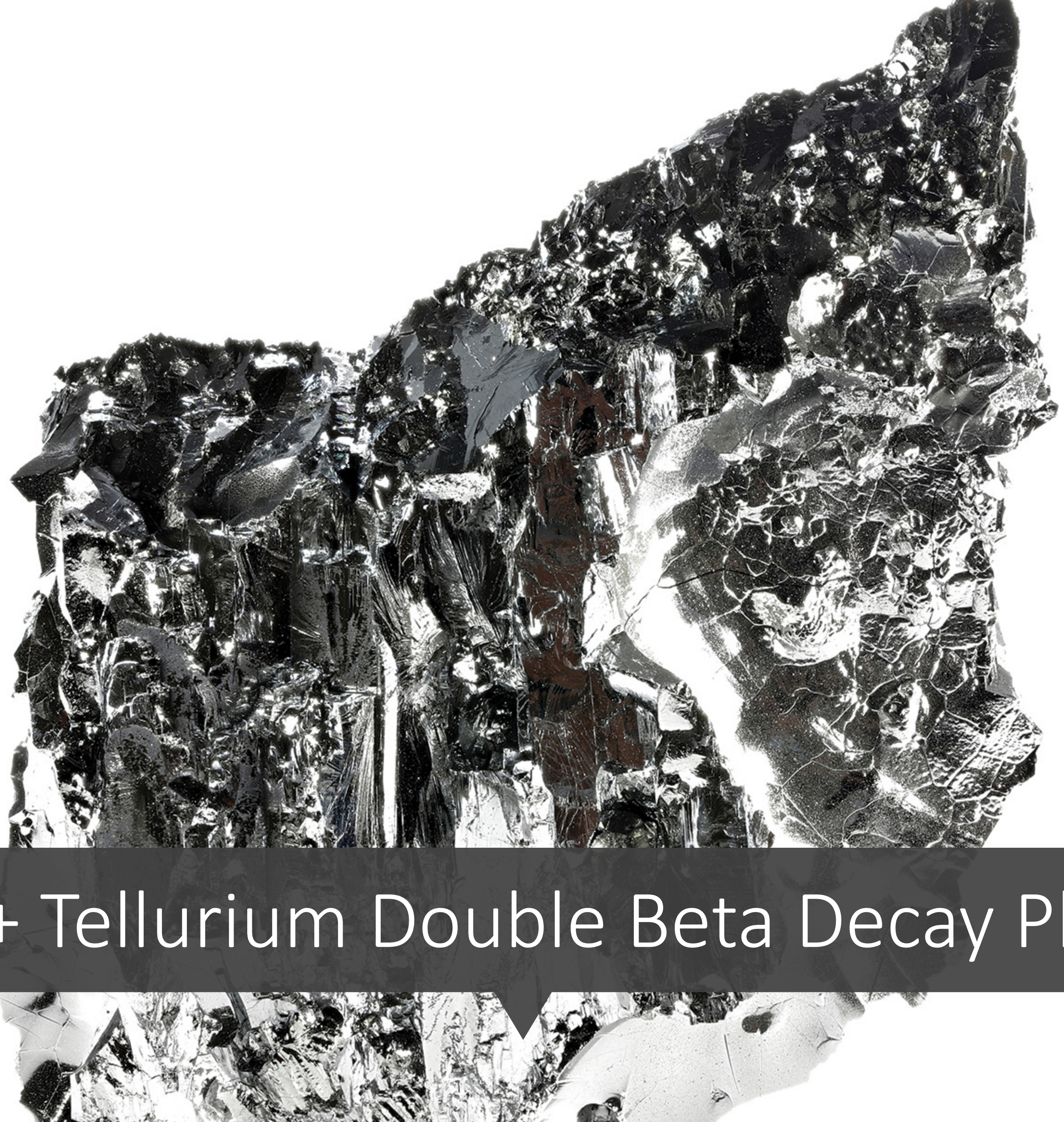






The advantages of a well-understood detector with very low backgrounds

- are being demonstrated!
- SNO+ has a diverse physics program that is being pursued.
- 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+…

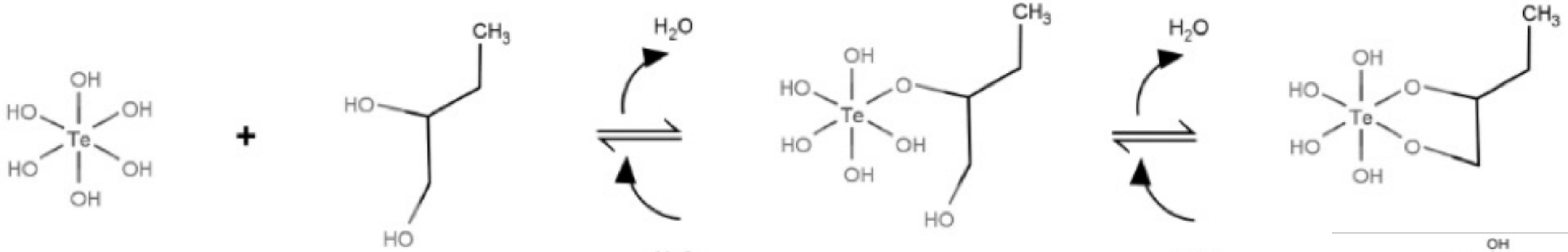


SNO+ Tellurium Double Beta Decay Phase

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*

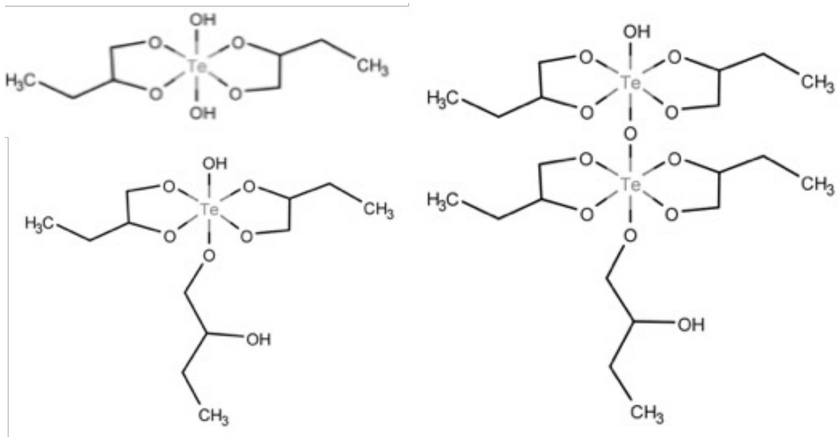
^{130}Te has 34% natural abundance = no costly or logistically difficult isotopic enrichment required



“Telluric Acid (TeA)”

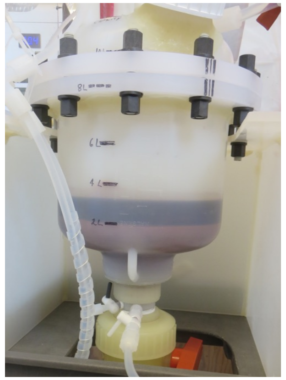
“1,2-Butanediol”

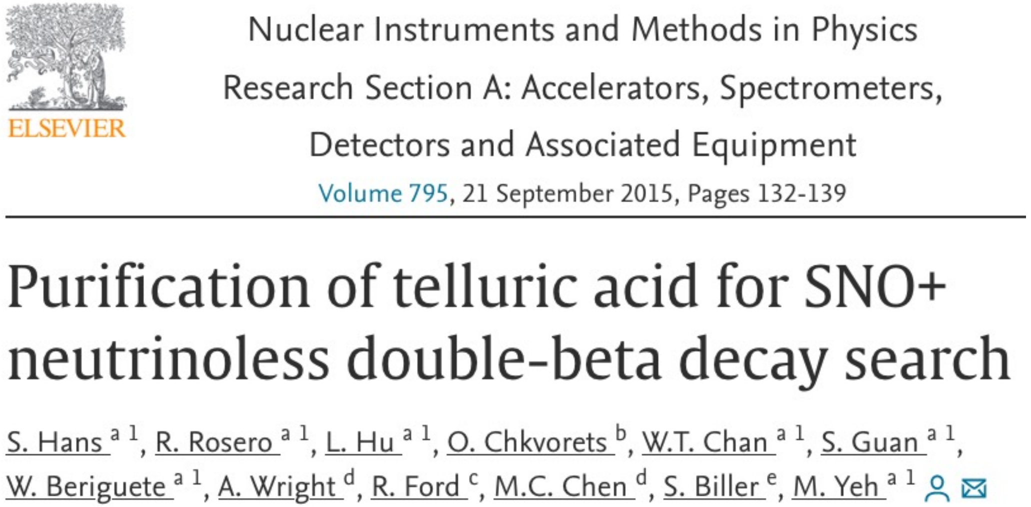
leading to tellurium-diol complexes that dissolve in LS



Novel Tellurium Purification and Tellurium Loading Techniques Pioneered by SNO+

Te purification technique established



ELSEVIER

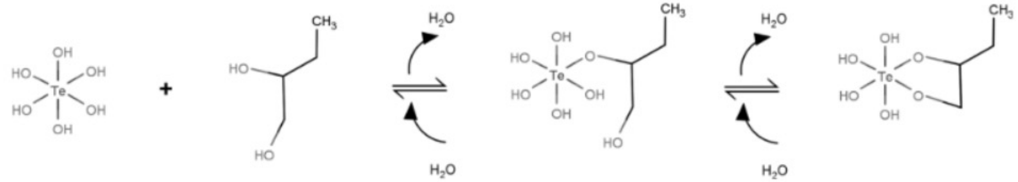
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

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



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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

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Tellurium Purification Process via pH Selective Telluric Acid Recrystallization

Telluric acid obeys the following equilibrium:

$$Te(OH)_6 \rightleftharpoons Te(OH)_5O^- + H^+$$

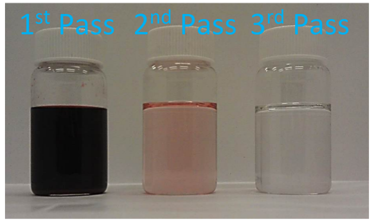
Insoluble

Soluble

pH determines the equilibrium state

Purification basics:

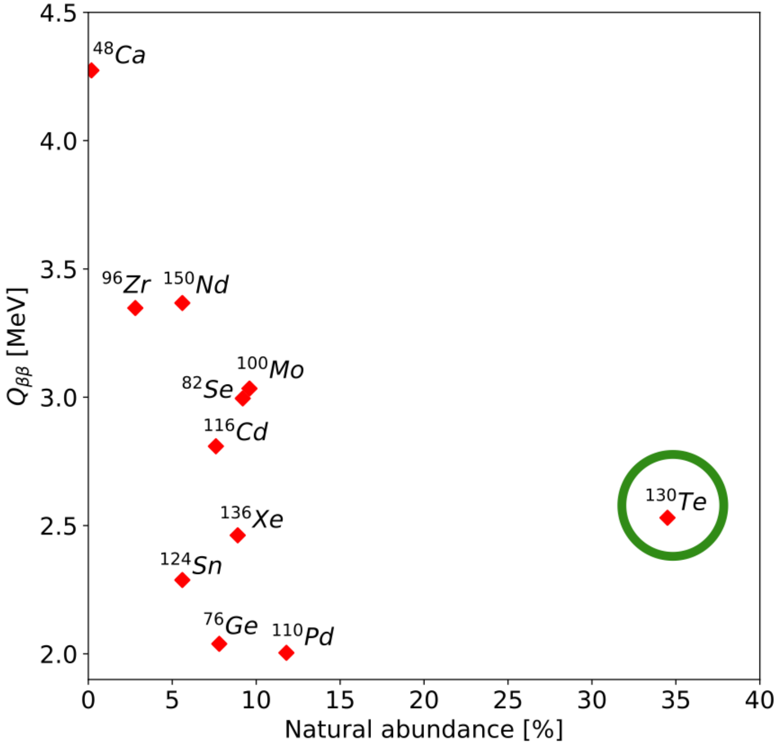
1. Dissolve telluric acid in water and filter it
   - Removes water insoluble impurities
2. Add nitric acid to force the telluric acid to recrystallize/precipitate, pump away the liquid and rinse
   - Removes acid soluble impurities



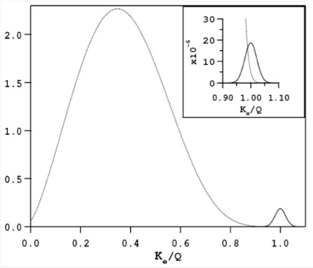
50kg pilot-scale

By “tuning” the process pH’s, this can be quite specific to telluric acid – most other chemicals are removed with high efficiency.

Tellurium for Double Beta Decay



^{130}Te & ^{136}Xe have the smallest 2νββ/0νββ ratio



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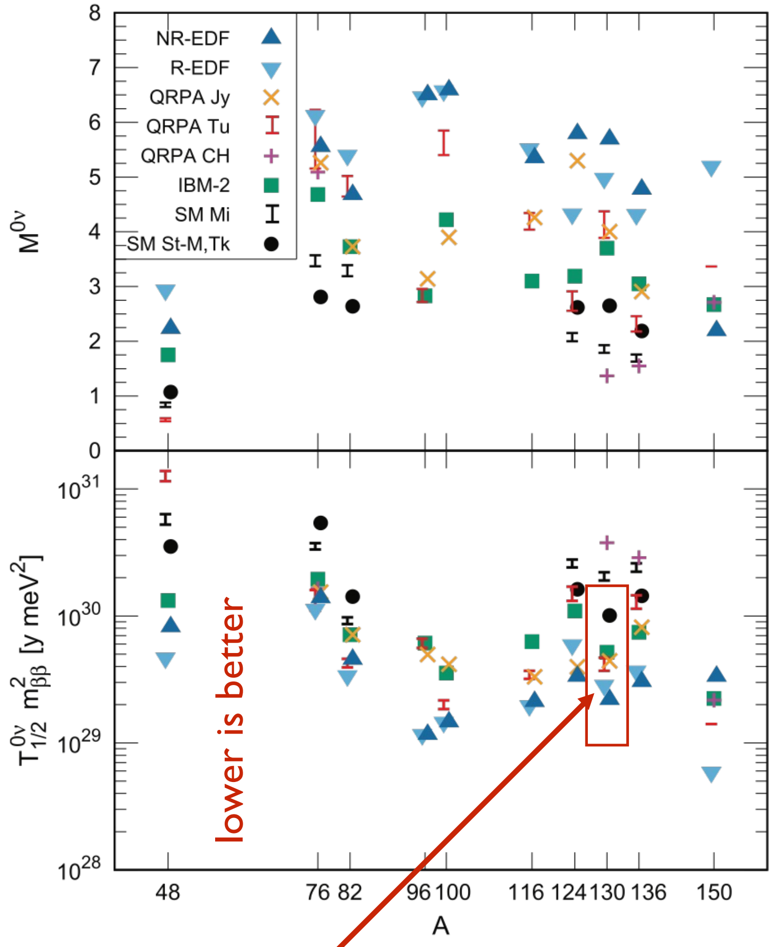


lower is better

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

Loaded Scintillator Approach to DBD

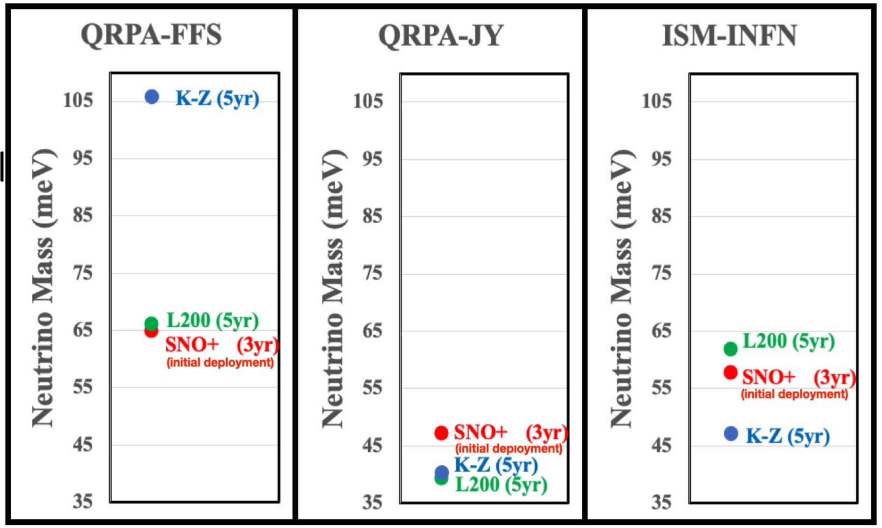
- Previous slide: “why tellurium?”
- This slide: “why in liquid scintillator?”

1. very low backgrounds: $5{\times}10^{-7}$ counts/keV/$\mathrm{kg}_{\text{fiducial detector}}$/yr
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!

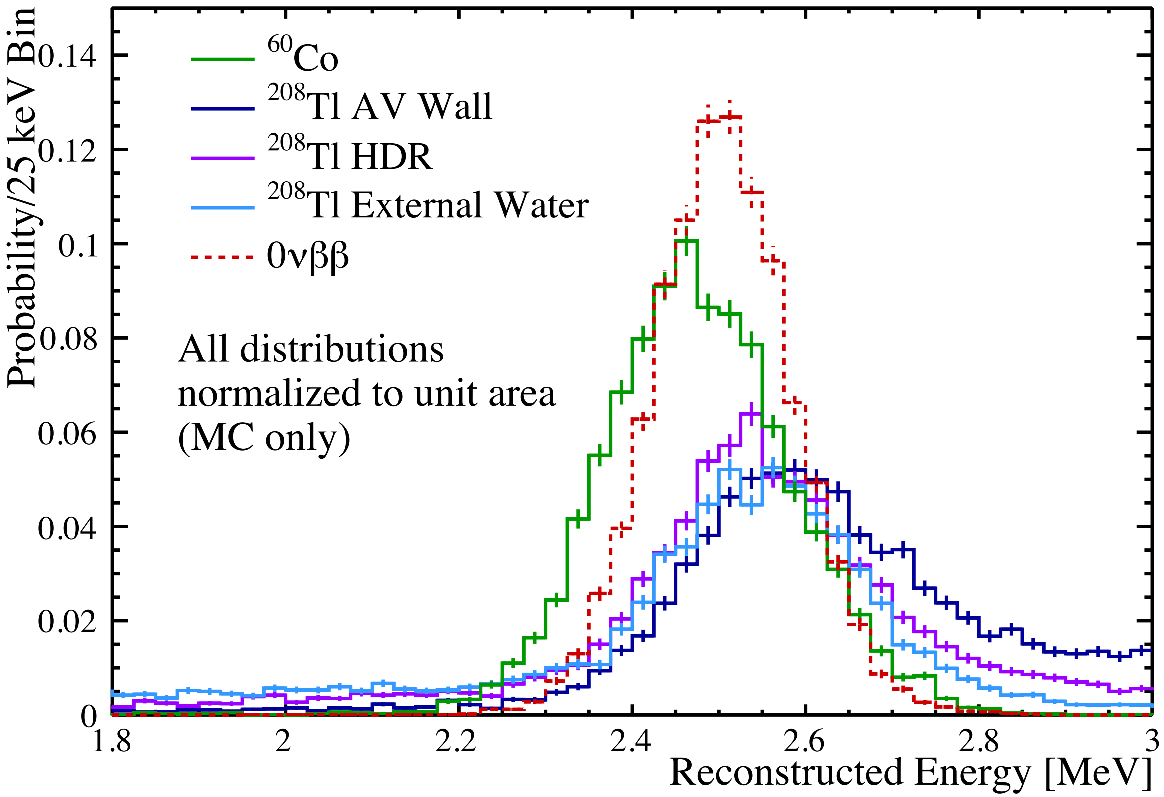
SNO+ Te DBD Additional Considerations

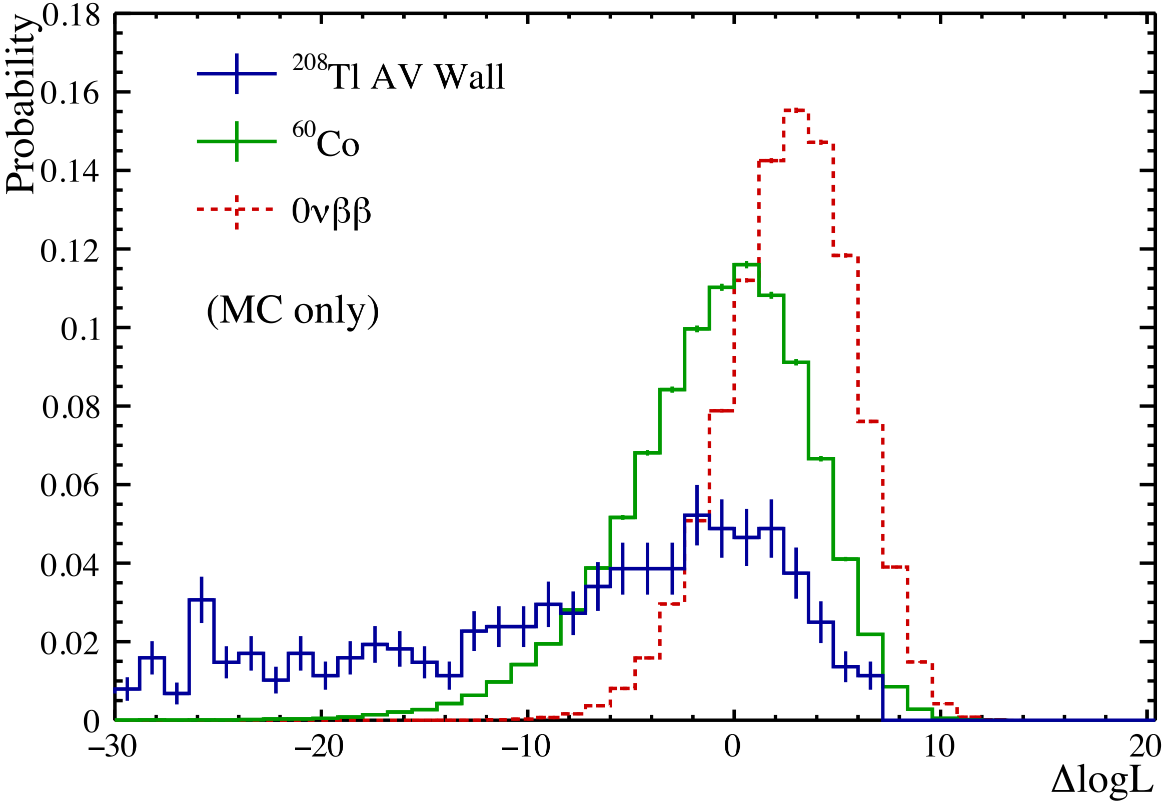
- ^{130}Te DBD is scalable, cost effective, unimpacted by logistics difficulties of isotope enrichment
- KL-Z 800 has world-leading sensitivity (upper limit 36-156 meV) and highlights the strength of the loaded LS DBD approach
- Complementarity of isotope
  - NME model dependencies
  - SNO+ sensitivity at %Te loading "fills the gap", before lar experiments come online
  - complementary isotope and approach
  - 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



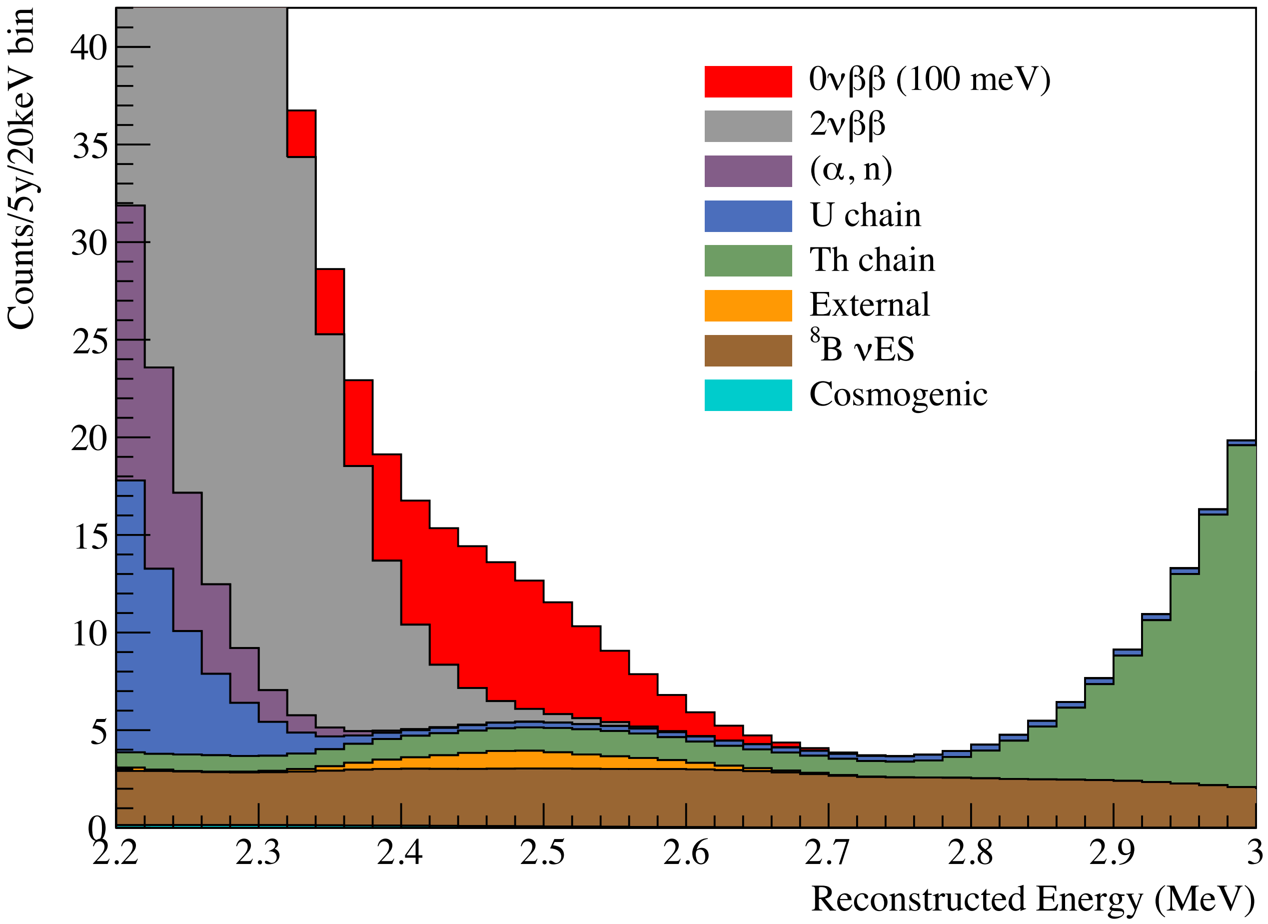
- SNO+ also has single-site/multi-site background constraining power

SNO+ Multi-site Background Likelihood Constraint

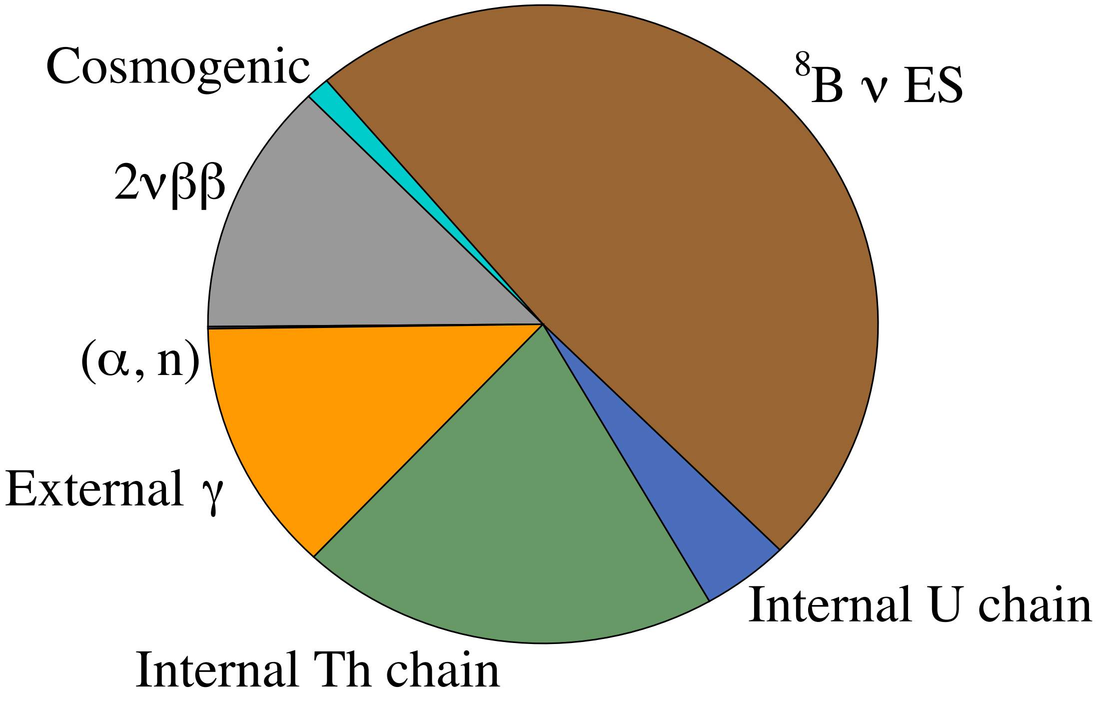




DBD Spectrum and Backgrounds Pie Chart



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



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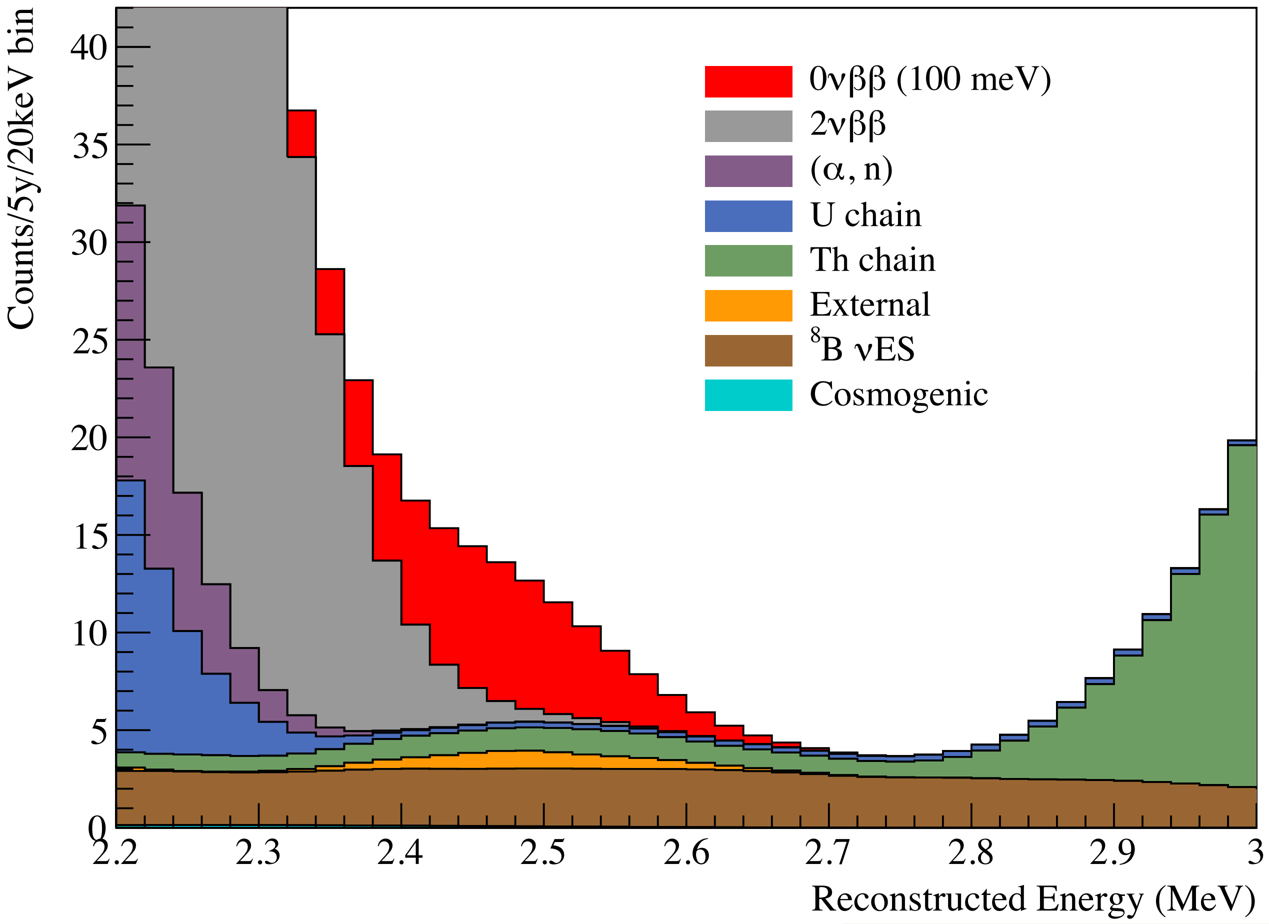

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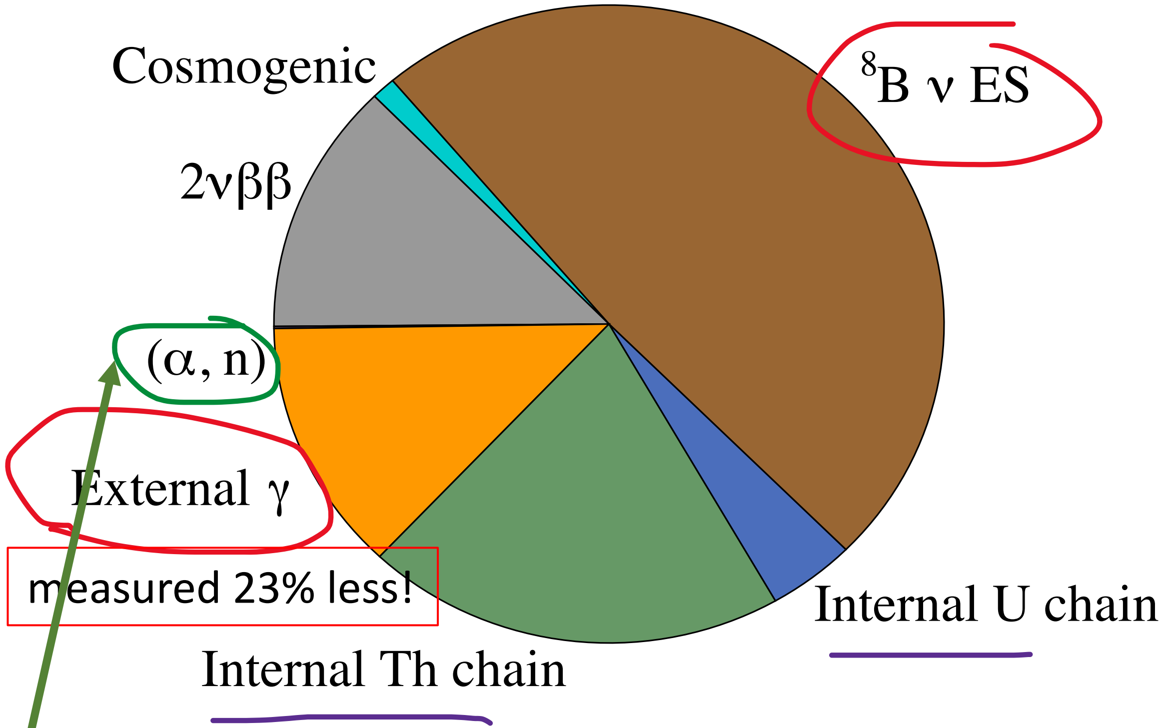


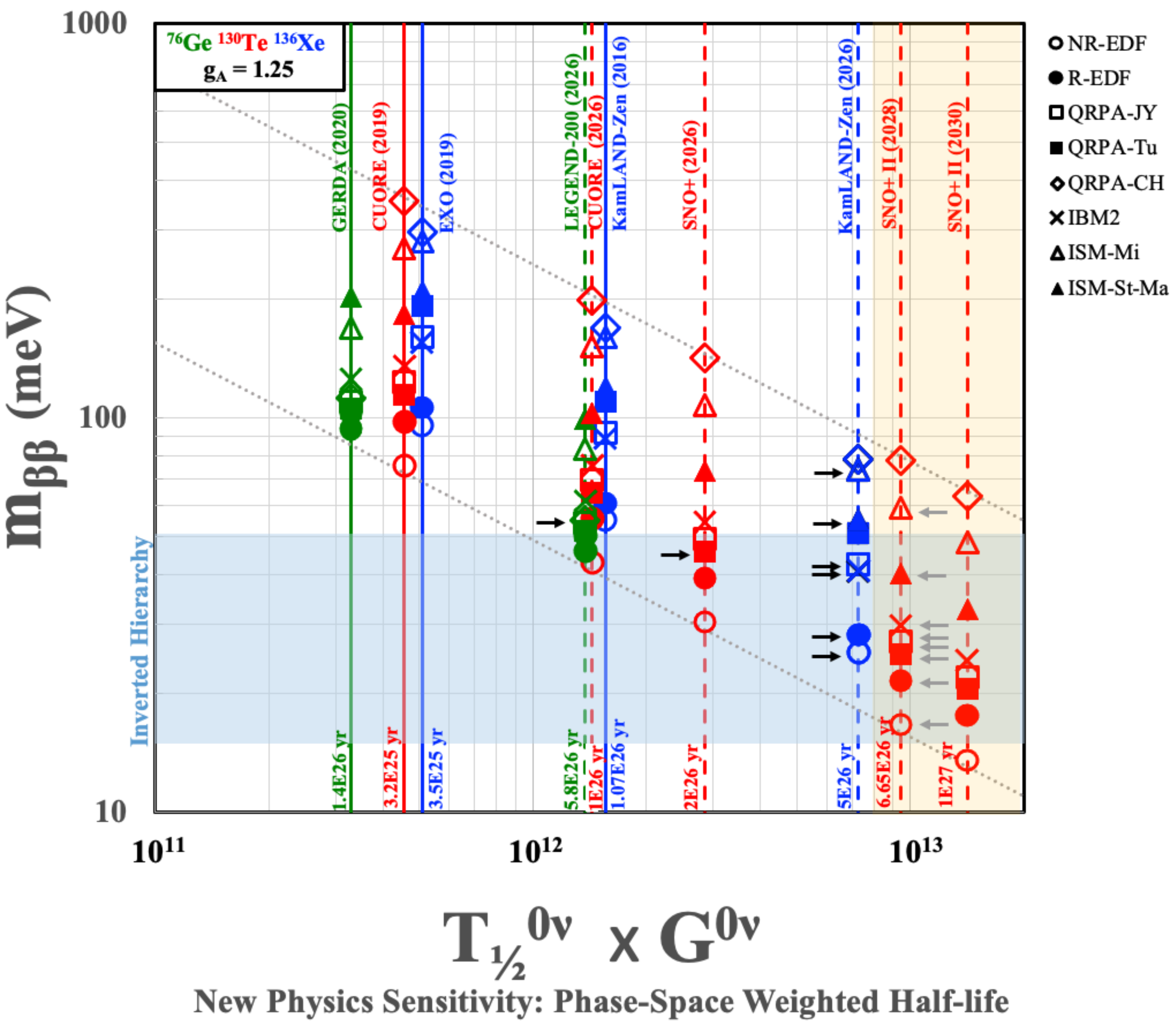
known

measured 23% 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)

Sensitivity



Status of SNO+ Te DBD

Tellurium systems are built and ready for operation!

TeA purification test batch (at full-scale) is being prepared and will start in the next few months

Telluric acid purification

Te-diol synthesis

Summary

- SNO+ is an operating liquid scintillator neutrino detector filled with LAB + 2.2 g/L PPO and taking data
- Diverse program of neutrino (and other) 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

SNO+

August 9, 2022