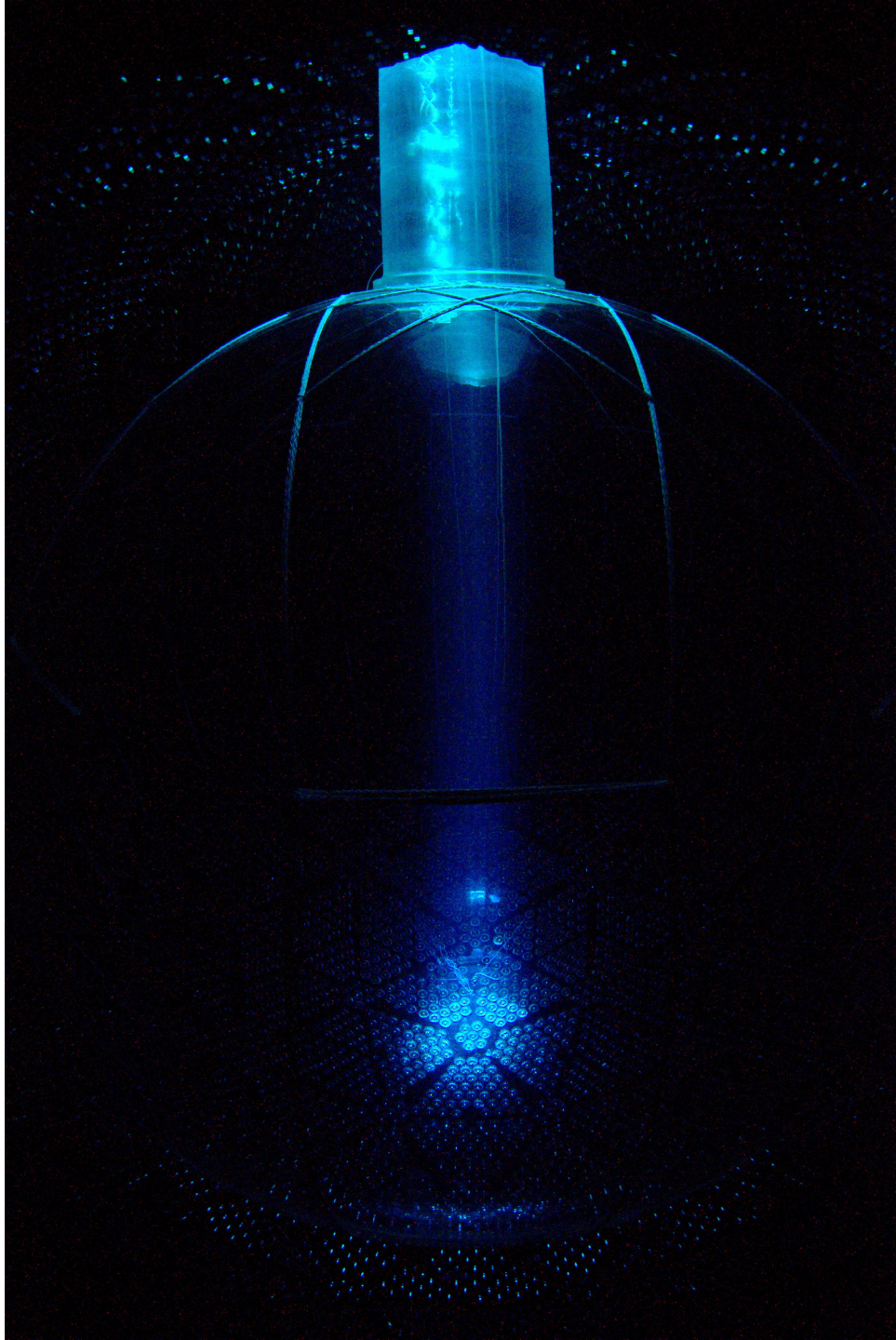
a talk with some historical recollections fitting for an anniversary symposium

IPP 50th Anniversary Symposium

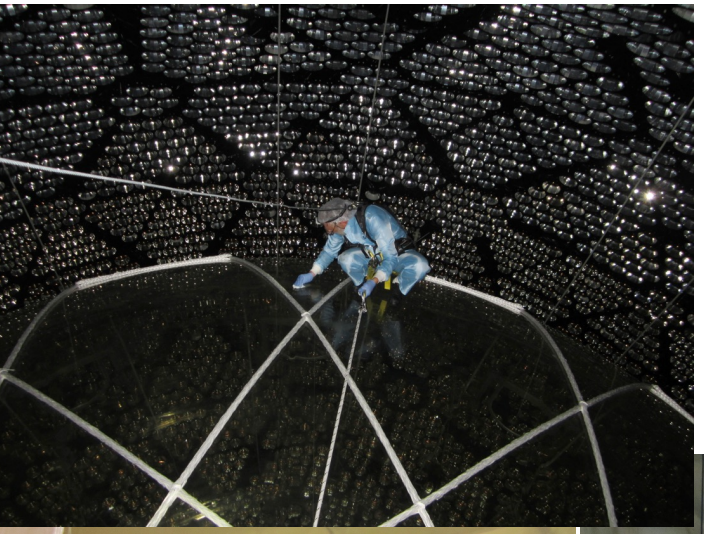
Mark Chen

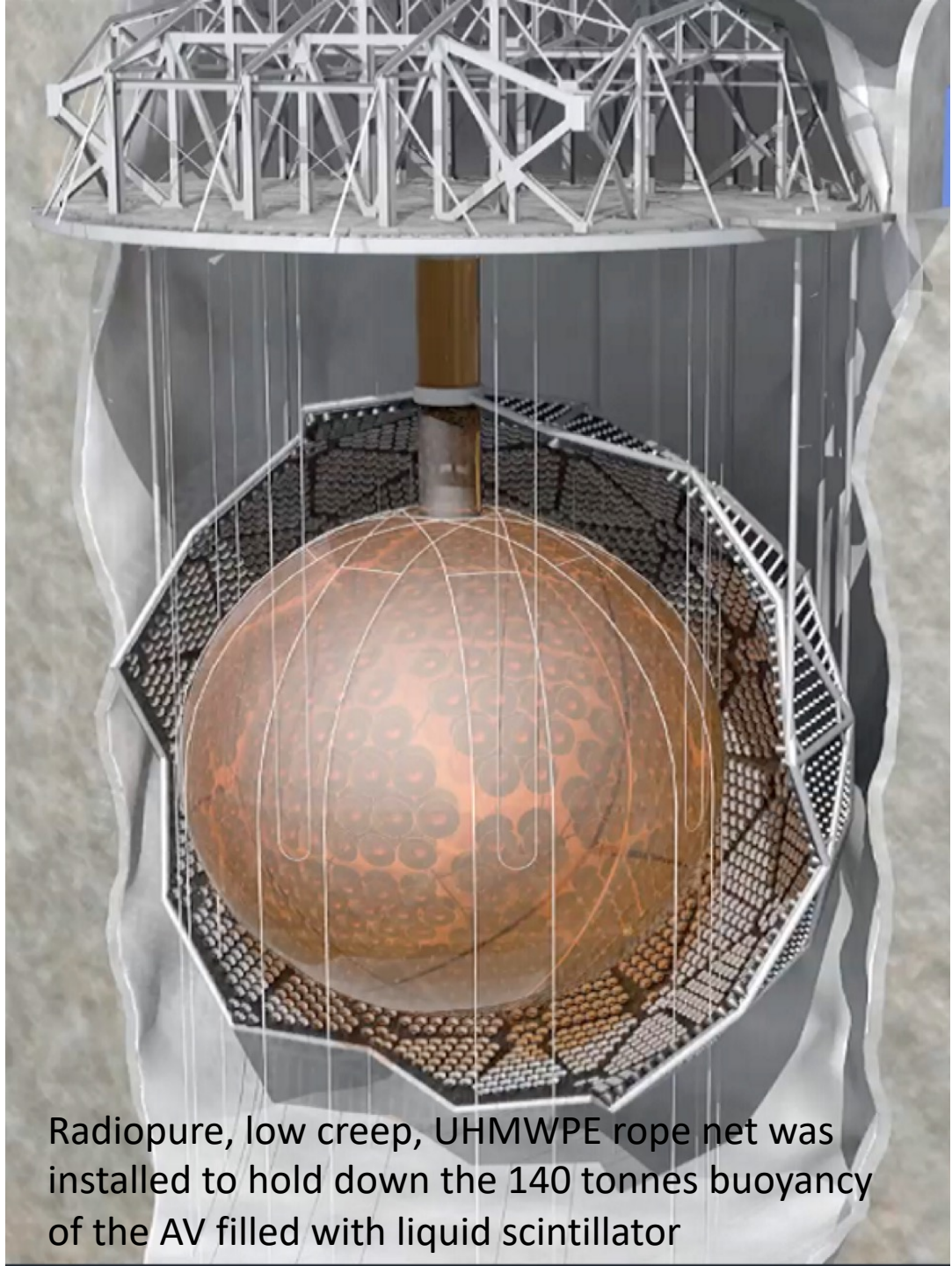
Queen's University and CIFAR

May 29, 2021



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…

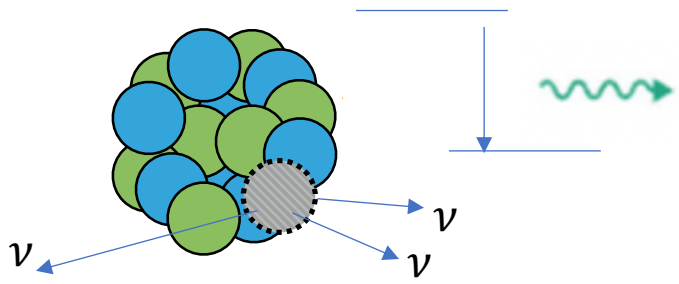
- SNO Cavity floor liner had been badly torn at the end of SNO; had to be remade (during SNO+ hold-down anchor installation)
- Anchor installation involved *drilling* into concrete and rock *inside an ultra-low background neutrino detector*
- Submersible pump that drained the SNO AV had self-destructed, covering the bottom, inner AV with dirty oil
- SNO Cavity walls had many leaks – SNO+ had to find these leaks paddling around in the Cavity in a raft, in low-light conditions – months of painstaking 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
  - recently updated in arXiv:2205.06400

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 and improved
upon existing limits by factor 3

- Solar neutrinos

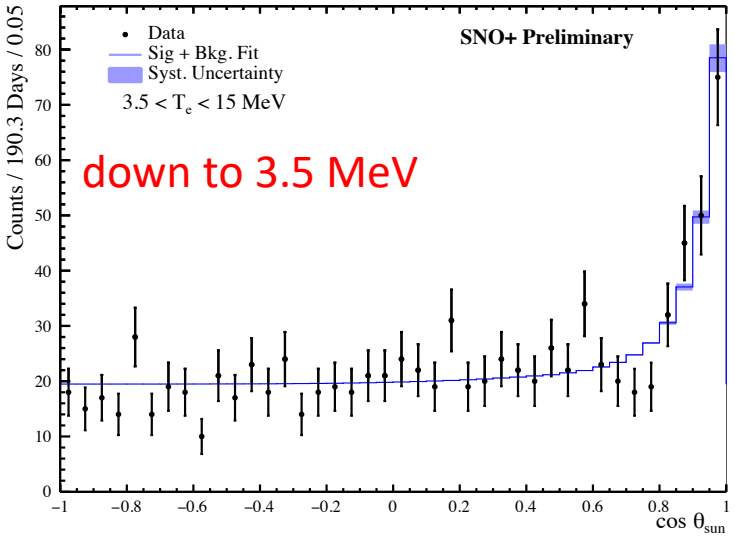
PHYSICAL REVIEW D **99,** 012012 (2019)

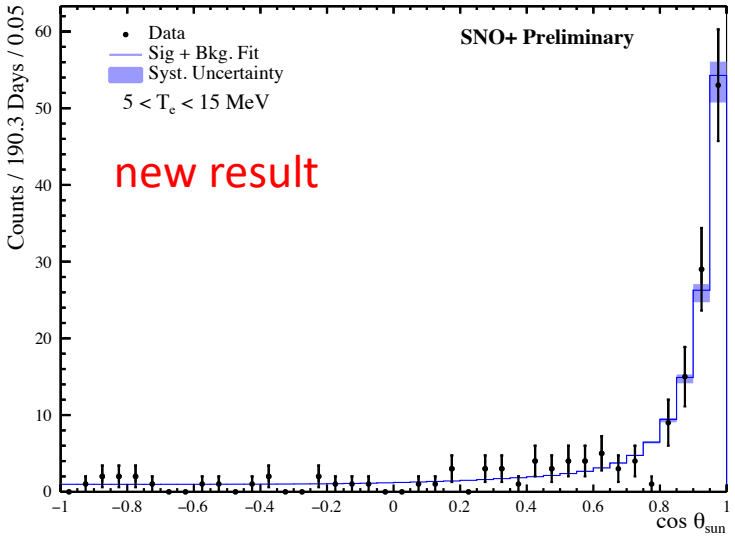
Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds

  - now with *even lower backgrounds*

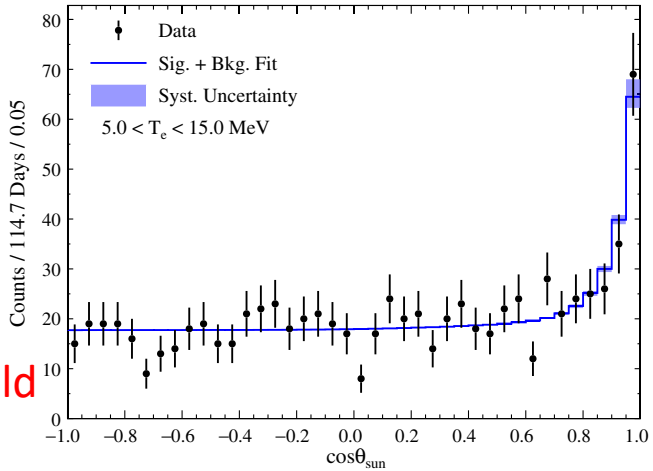
- First observation of reactor $\bar{\nu}_e + p \rightarrow e^+ + n$ events using *pure* water (undoped)
  - publication being prepared; detection of 9 and 10 events in two distinct analyses (BDT and likelihood) with >3 sigma significance
  - made possible by ~50% neutron detection efficiency (highest in a water Cherenkov detector)

SNO+ ^{8}B solar neutrinos in water



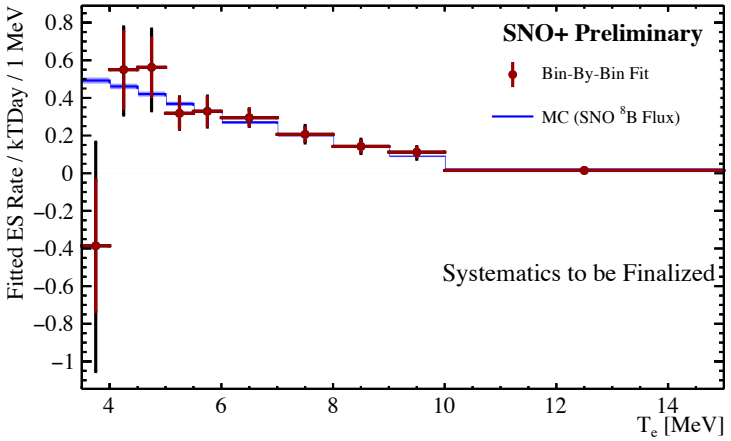


same threshold



From our 2019 paper

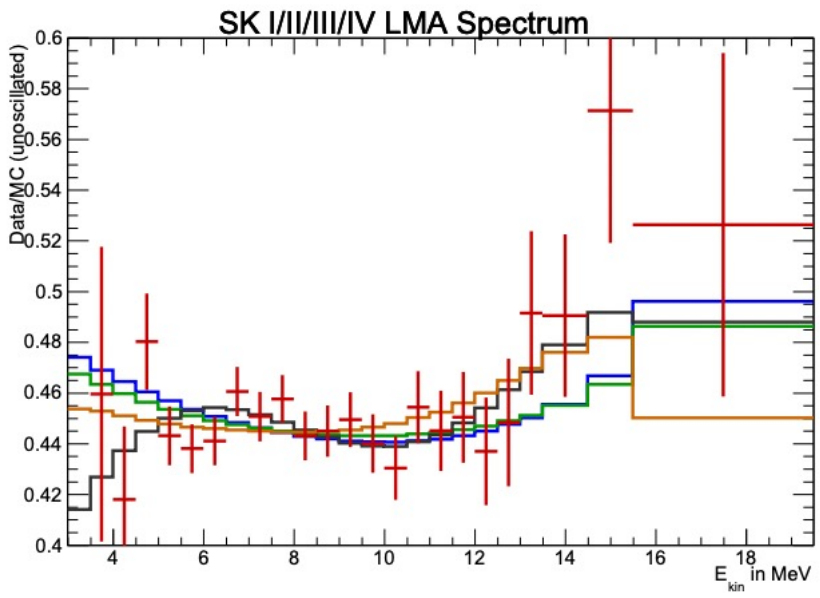
Our latest results with data from the extended water phase, with ~1/10 Rn levels (new SNO+ cover gas system)

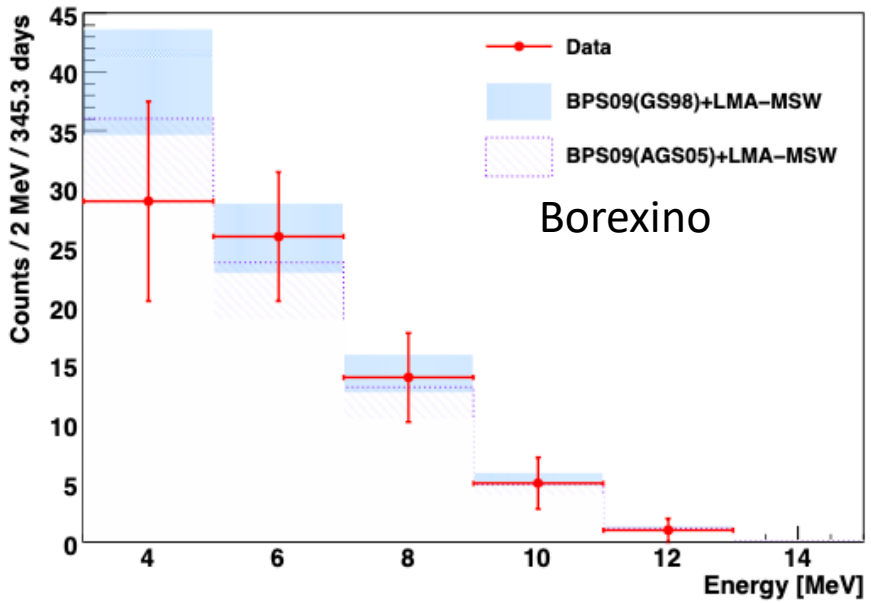


Radiogenic backgrounds are very low in SNO+.

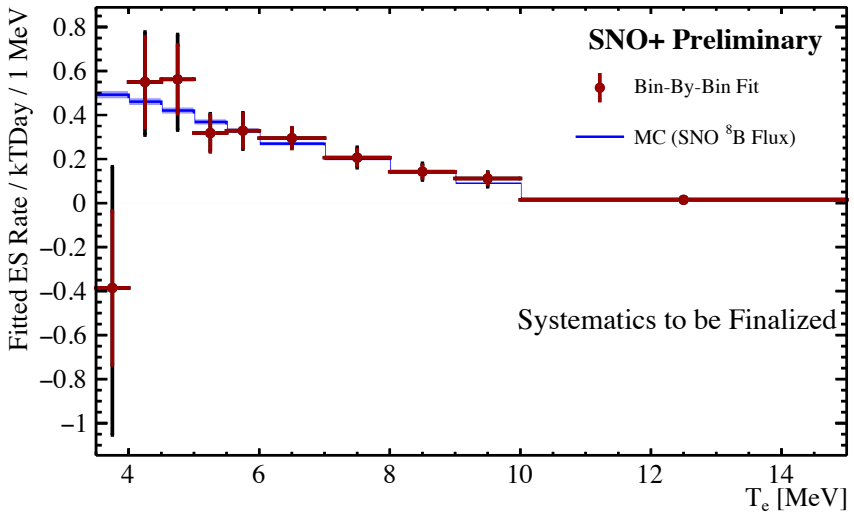
The deep location 6000 m.w.e. greatly suppresses cosmogenic backgrounds (e.g., factor ~450 muon flux reduction compared to KamLAND or Super-K).

It's interesting that nearly all experiments have their lowest energy bin containing fewer events than expected…
Nobody observes the rise in survival probability predicted for LMA MSW.

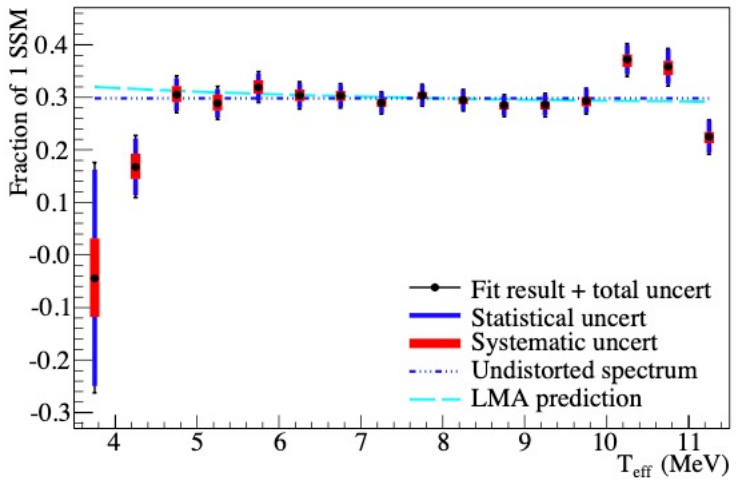




Not claiming this is anything; just noting it makes it very interesting to see what SNO+ scintillator will measure down at and below 3.5 MeV



SNO LETA



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

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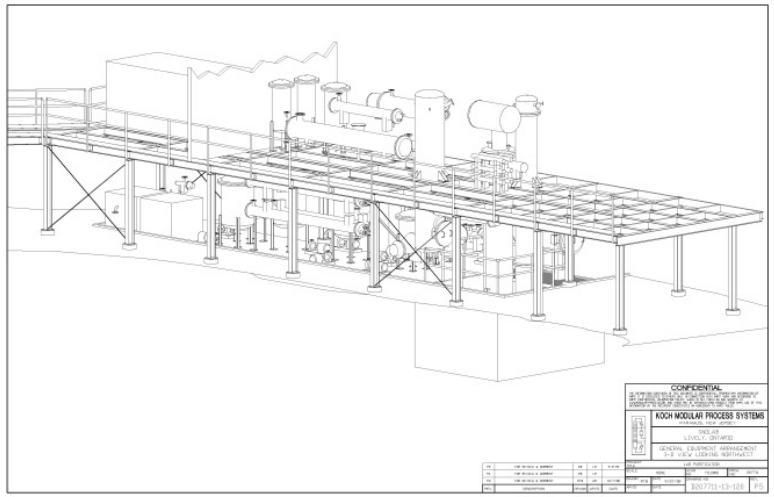
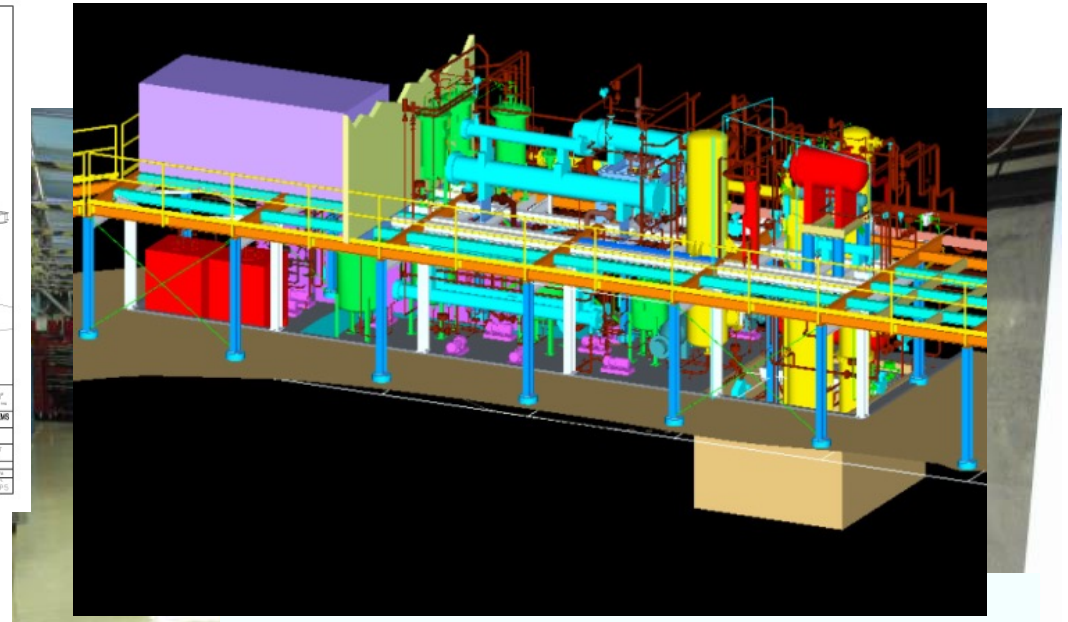
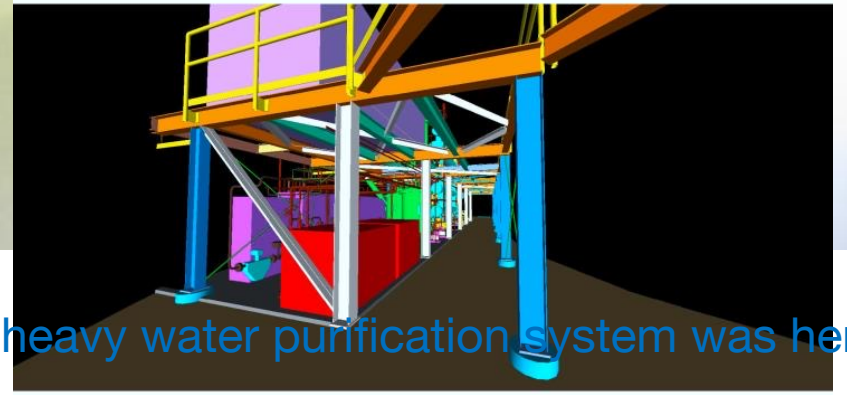
  stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression







the SNO heavy water purification system was here


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)

It’s not just 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

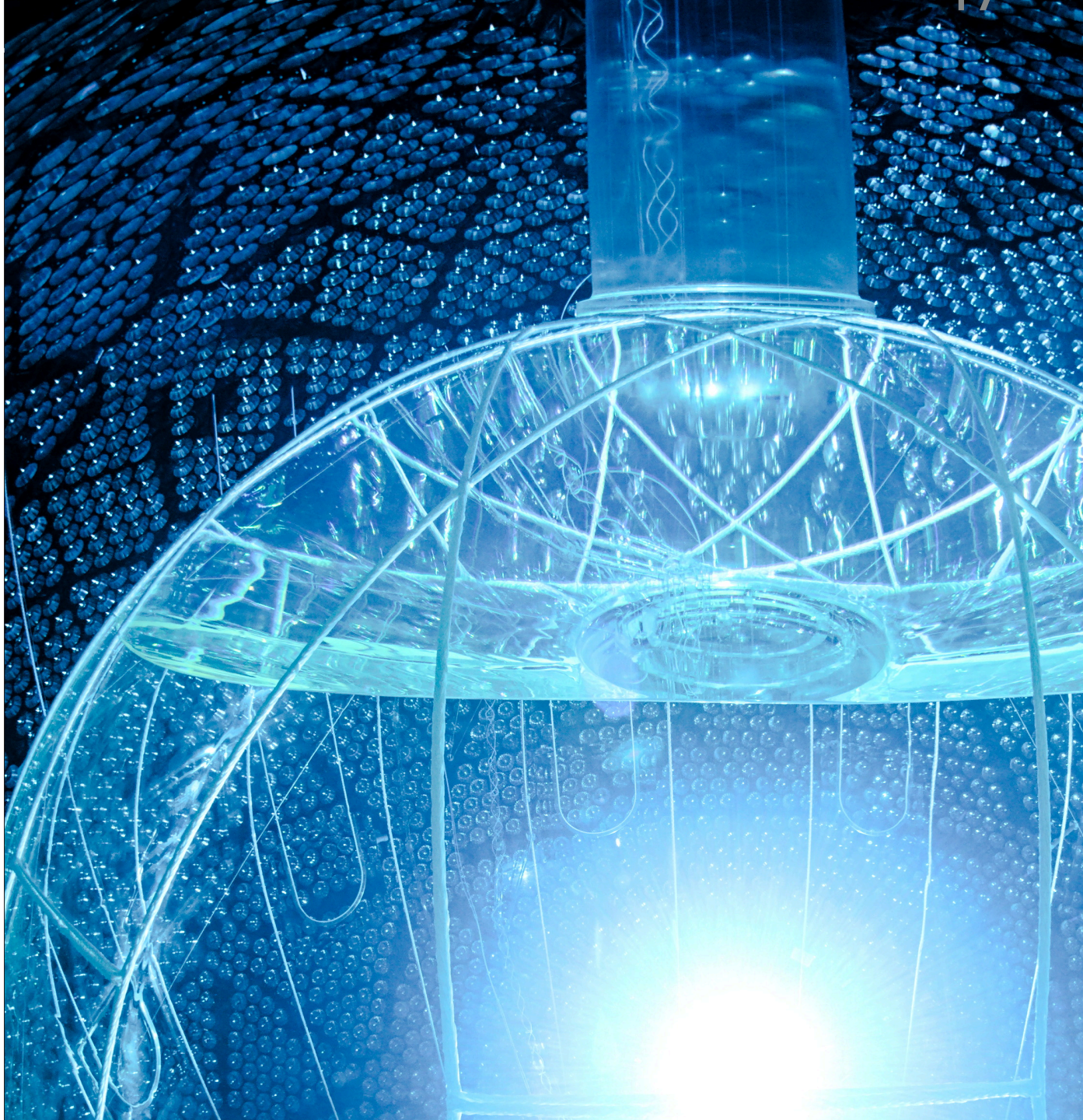
$(4.7\pm1.2)\times10^{-17}$ g_U/g_{LAB}

^{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)

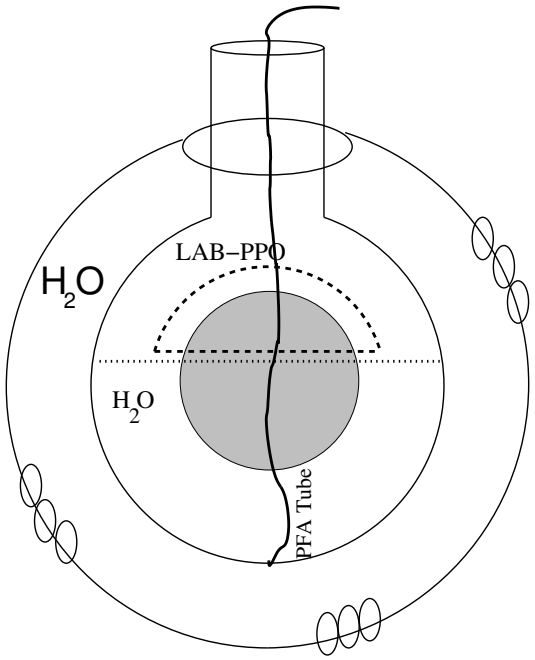
- Optical properties of LS 👍
- Also physics from SNO+ partial fill…

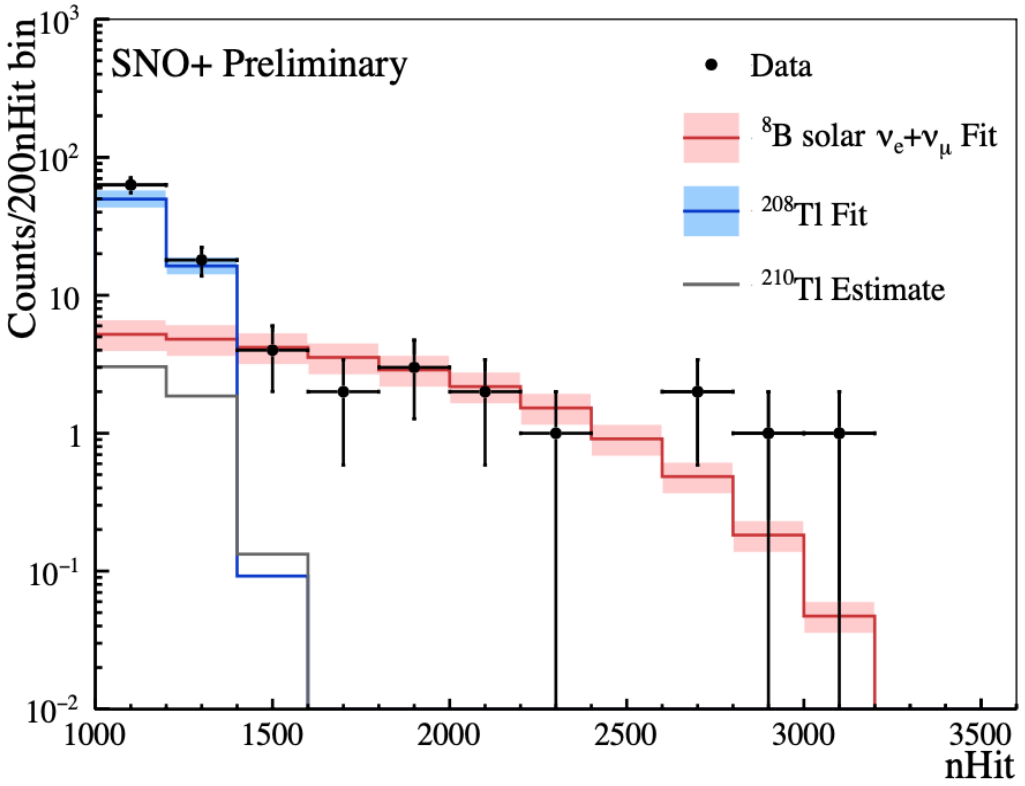


Partial-fill data taken in 2020

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





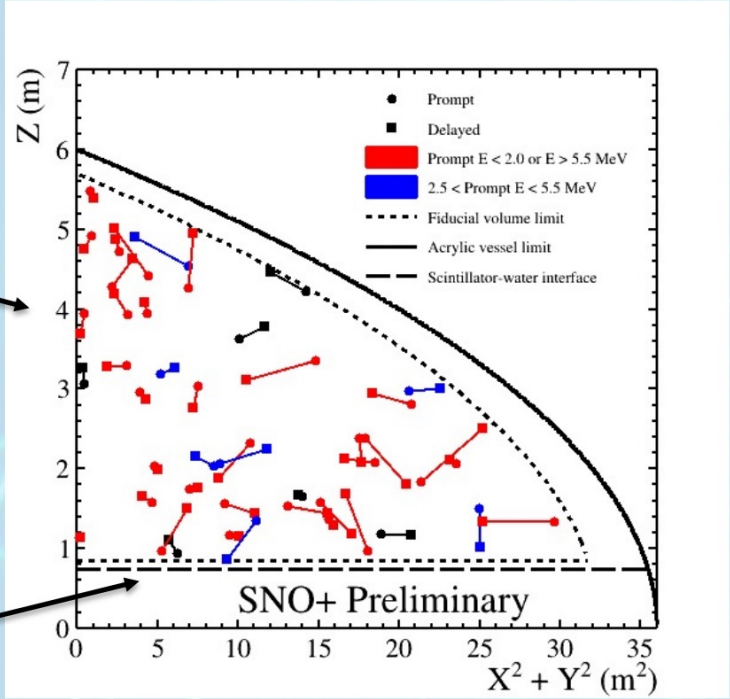
Partial-fill data taken in 2020

SNO+ reactor antineutrinos in partial-fill

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

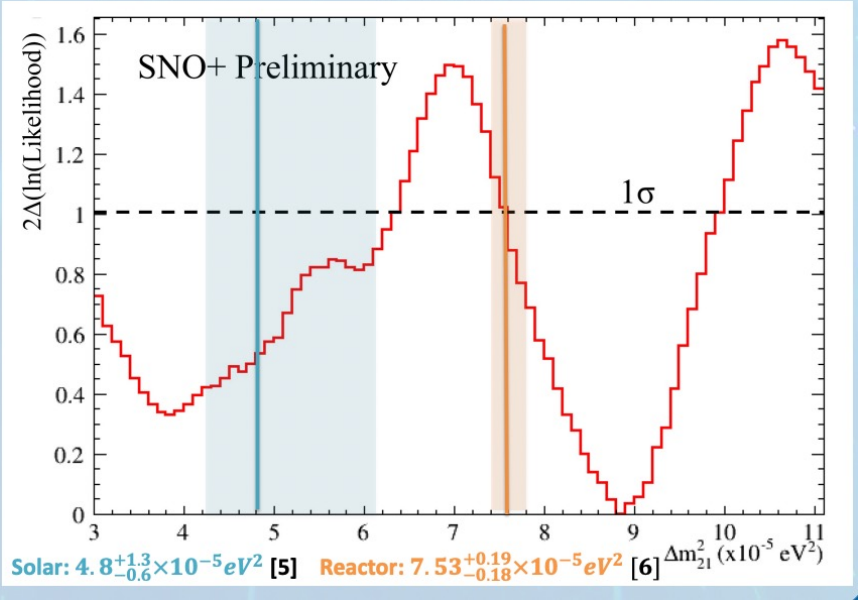
Events uniformly distributed in detector

Fiducialisation to reduce background events from acrylic



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

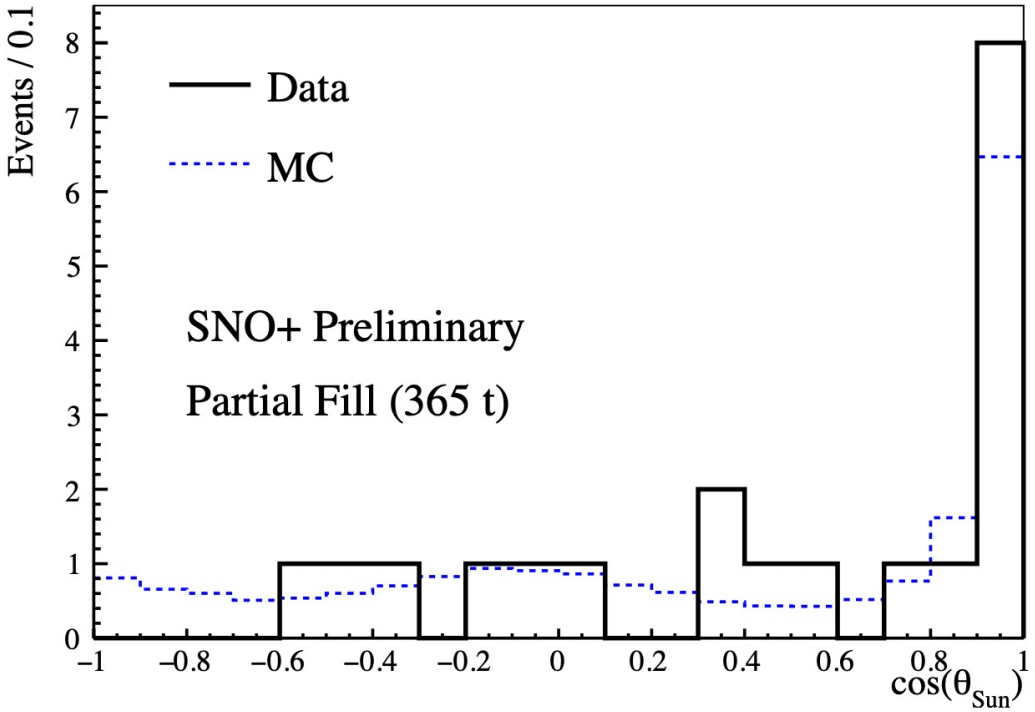
Δm^2_{21} likelihood space for observed IBD candidates



Another SNO+ Result – a First

Event-by-event direction reconstruction of solar neutrino events in SNO+ (low PPO ~0.5 g/L)

- recently, Borexino published the observation (*a posteriori*) of a correlation between PMT hits in the forward direction caused by the Cherenkov light produced by ^{7}Be solar neutrinos in liquid scintillator
- the SNO+ result is different: with low PPO, each recoil electron event's direction can be reconstructed by fitting to a pdf using Cherenkov+scintillation light combined



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

SNO+ is currently looking at directionality in 2.2 g/L PPO LS in full fill; looks somewhat promising…

There is quite a bit of interest in the field in Cherenkov-scintillation directionality

Publication being prepared

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 by SNO+ (with assistance from 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, topping up the concentration of PPO in the detector LS to 2.2 g/L

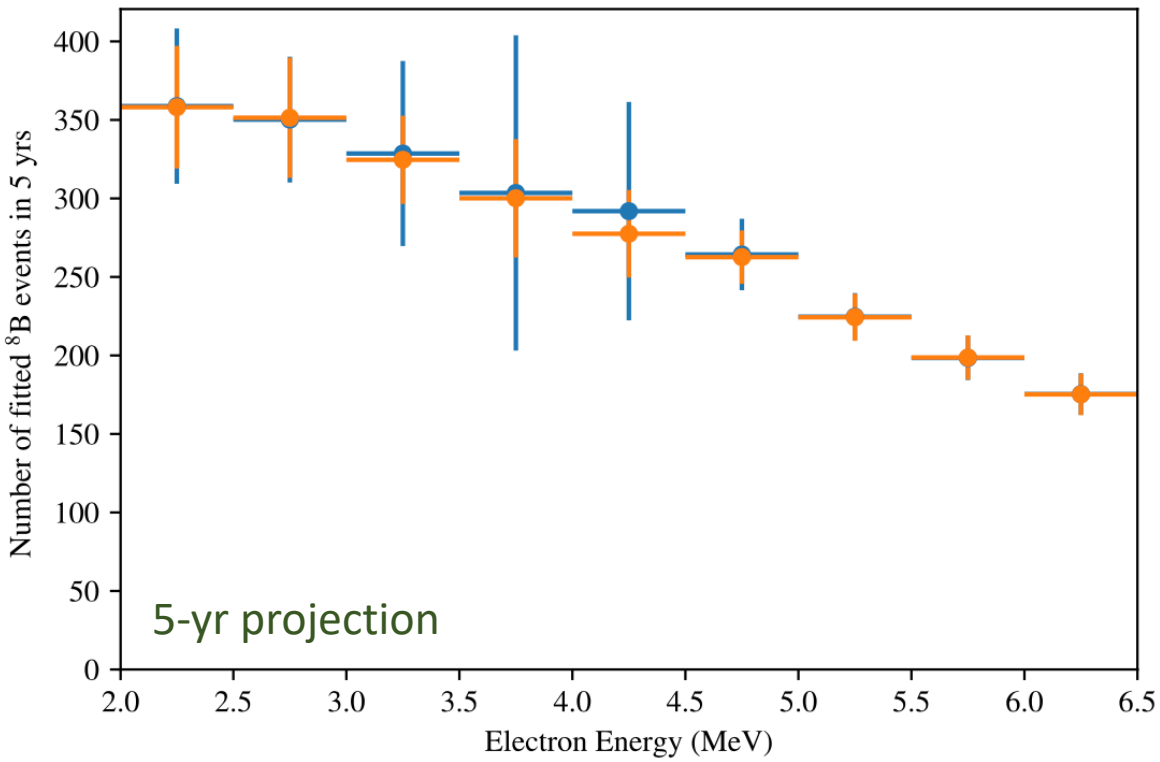
Truly a monumental effort by SNOLAB and SNO+ during the pandemic!

In April 2022, we just concluded scintillator PPO top-up operations – the detector is settling down and Rn backgrounds are decaying…

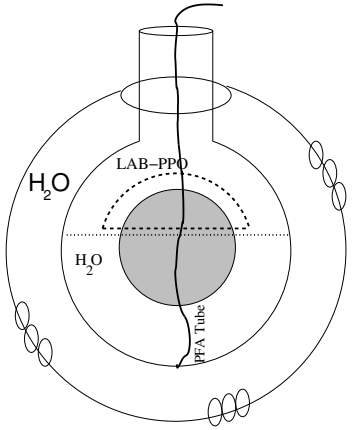
SNO+ Scintillator Phase

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)

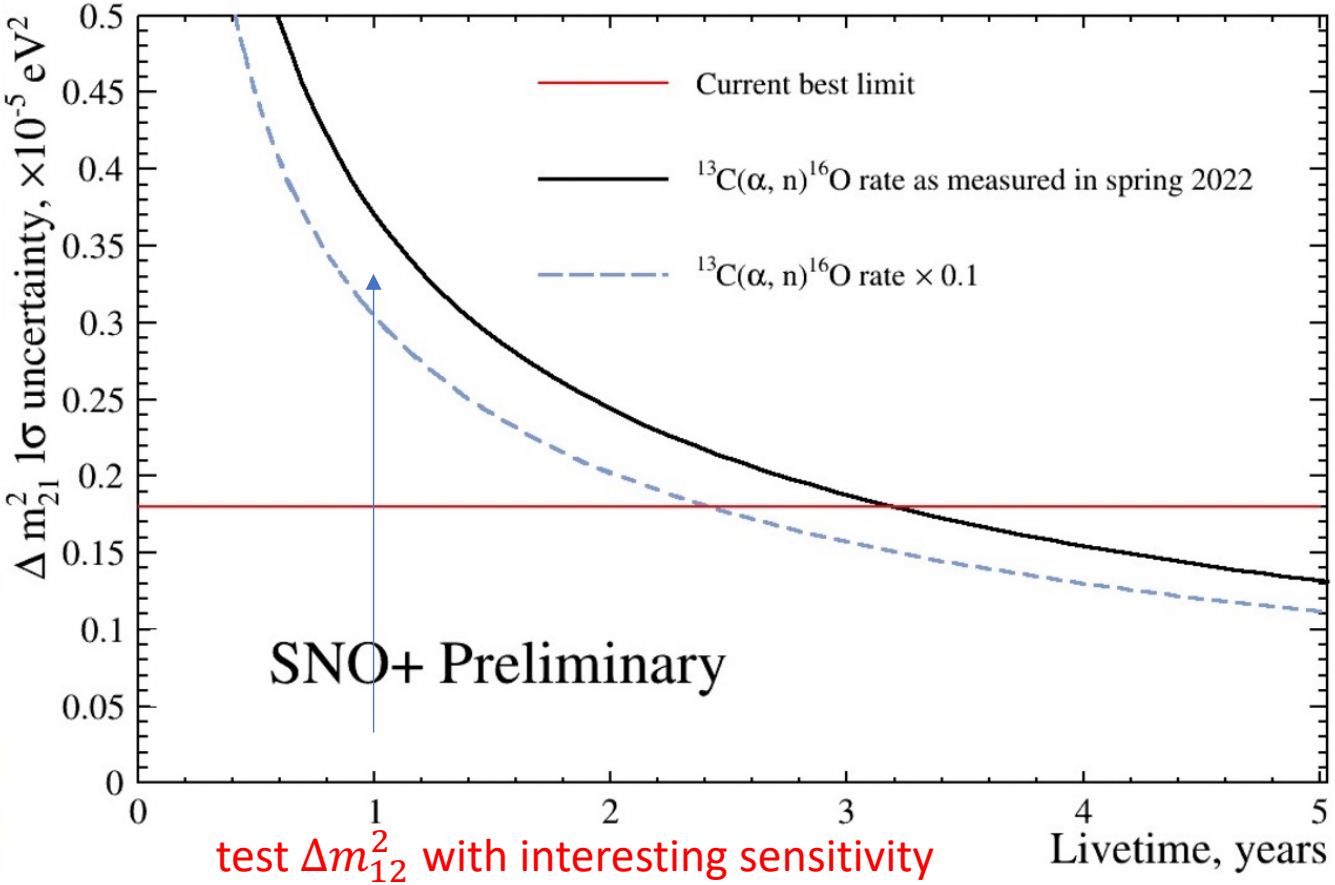


Blue U and Th at partial-fill levels
Orange U and Th below 10^{-17} g/g

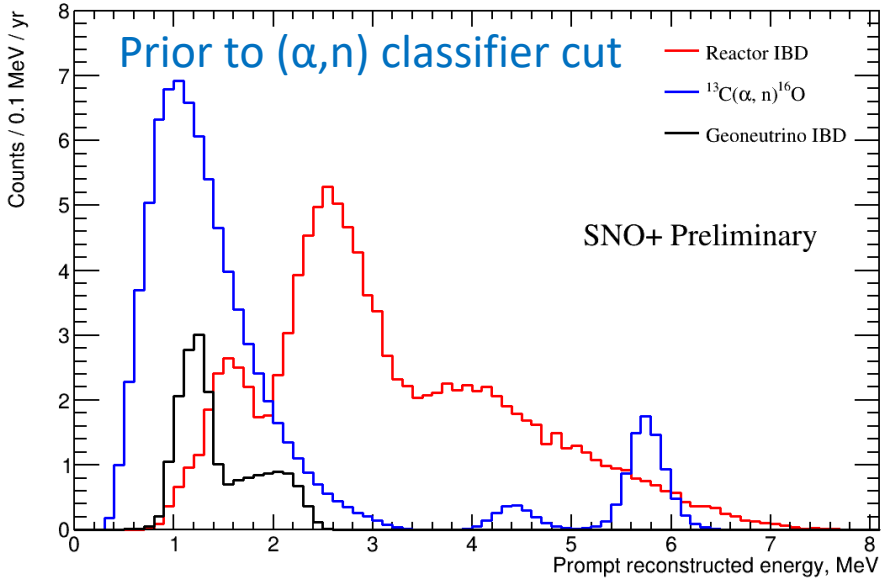


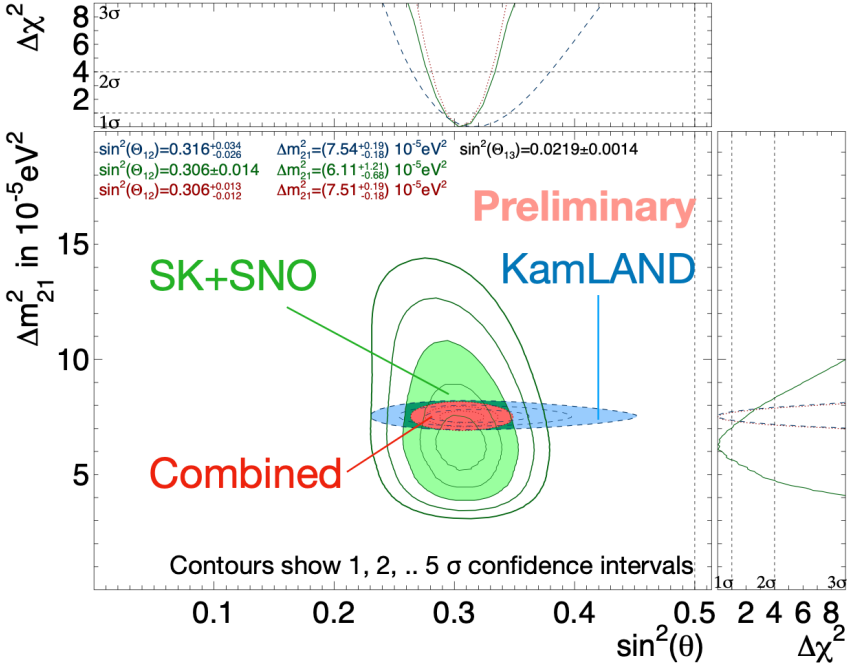
Reminder: partial-fill was sub-optimal; full detector expectation is lower Rn (U/Th)

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



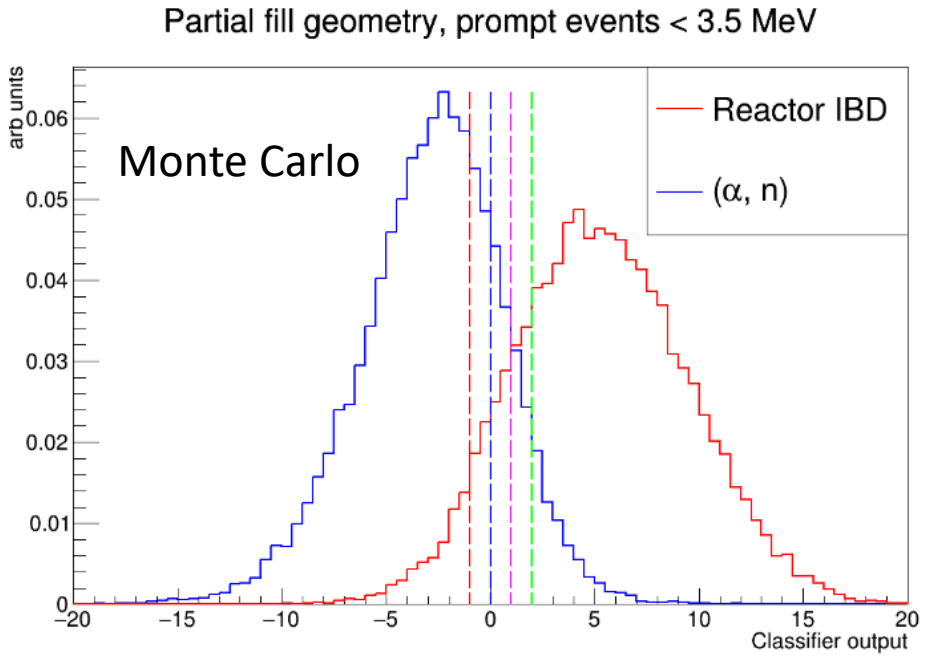
test Δm^2_{12} with interesting sensitivity already after 1 year (shape is more important than rate) to distinguish 4.8 from 7.5 ($\times 10^{-5}$ eV²)

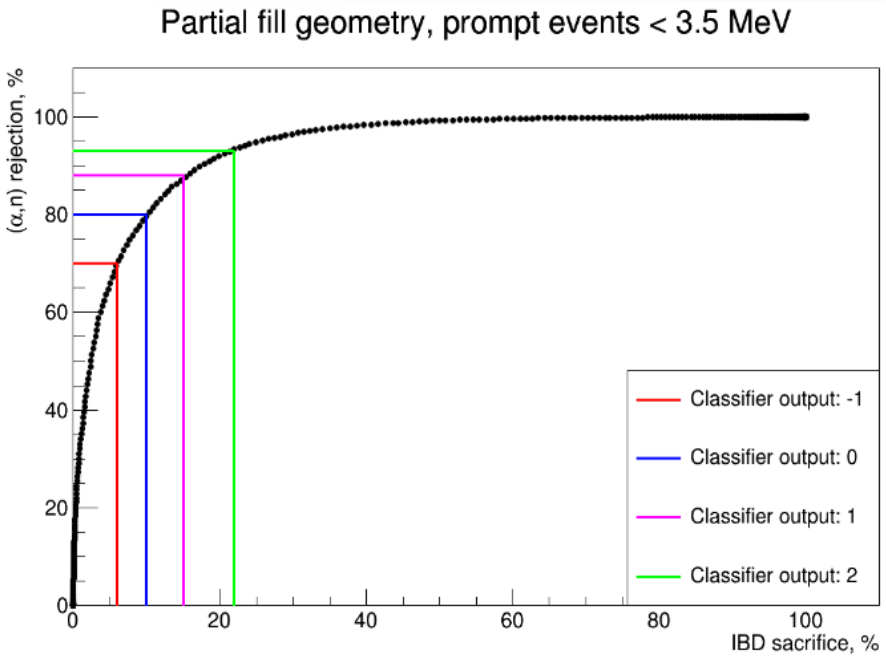


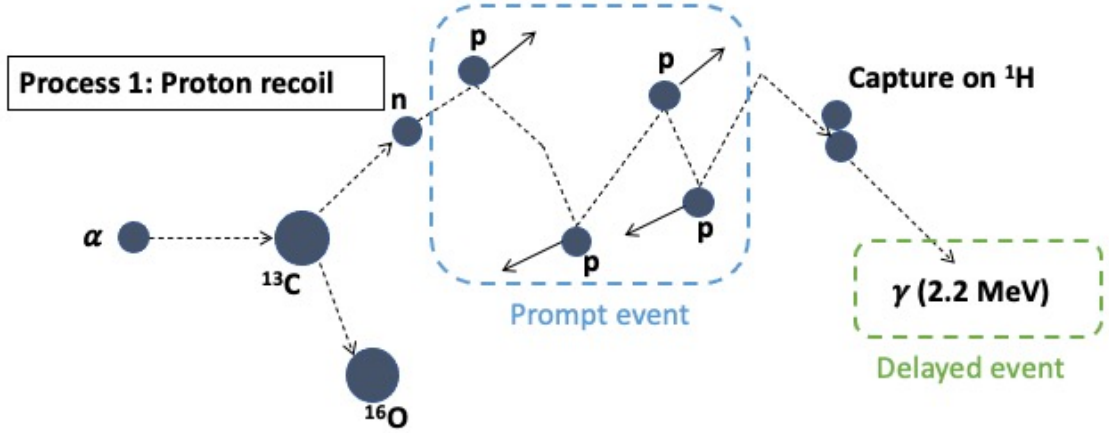


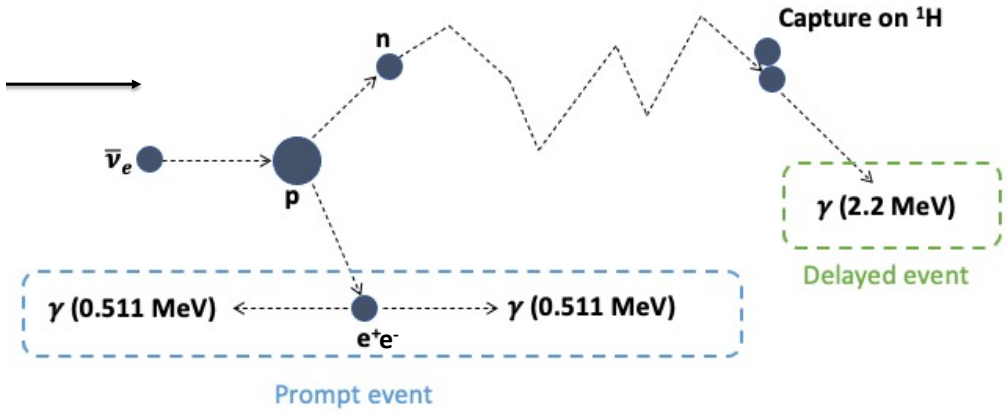
physics motivation for reactor neutrino oscillation studies

(α,n) Classifier is Effective (as modelled in partial-fill)



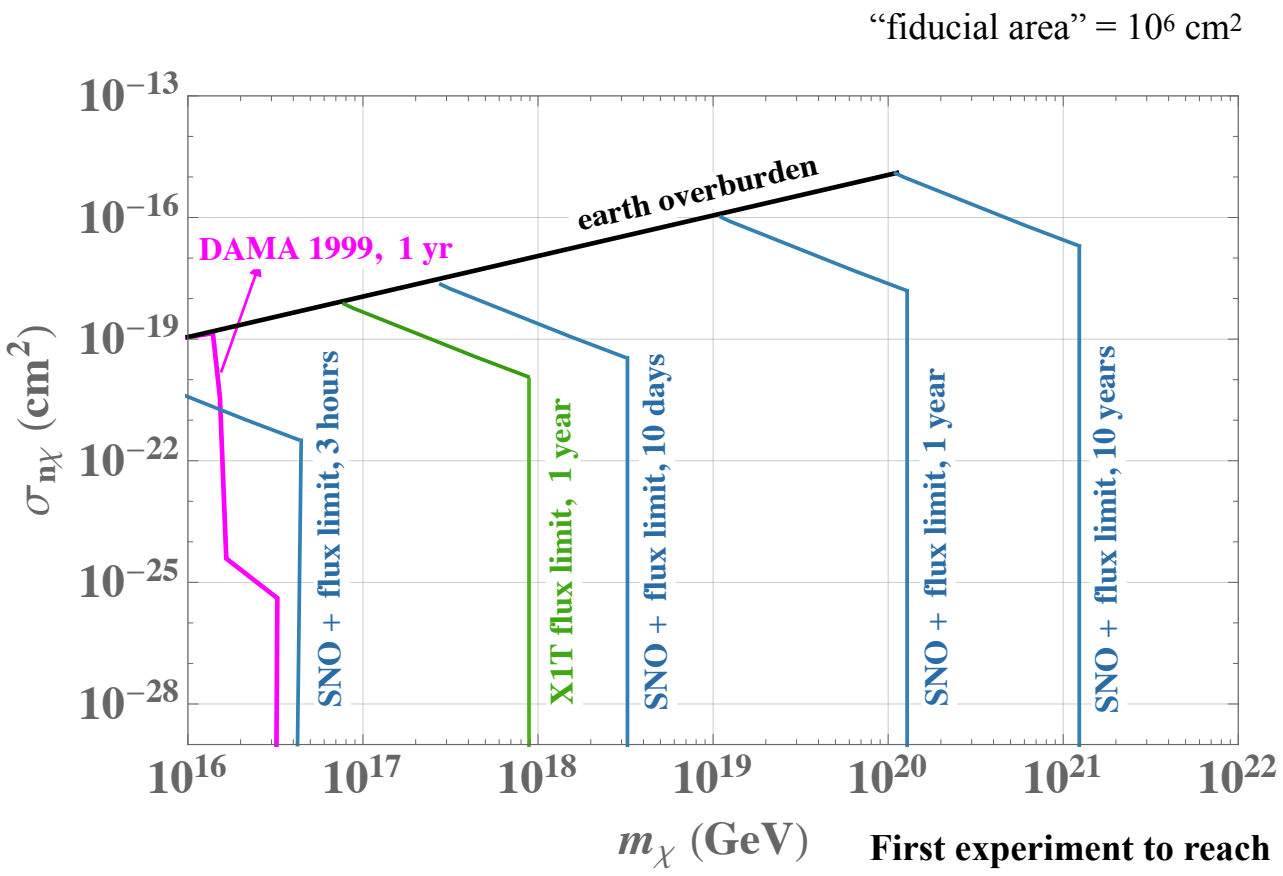






For some exotic dark matter models, SNO+ has some capability to probe further than others have or can…

MIMPs in SNO+



First experiment to reach Planck mass!

figure from N. Raj talk

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

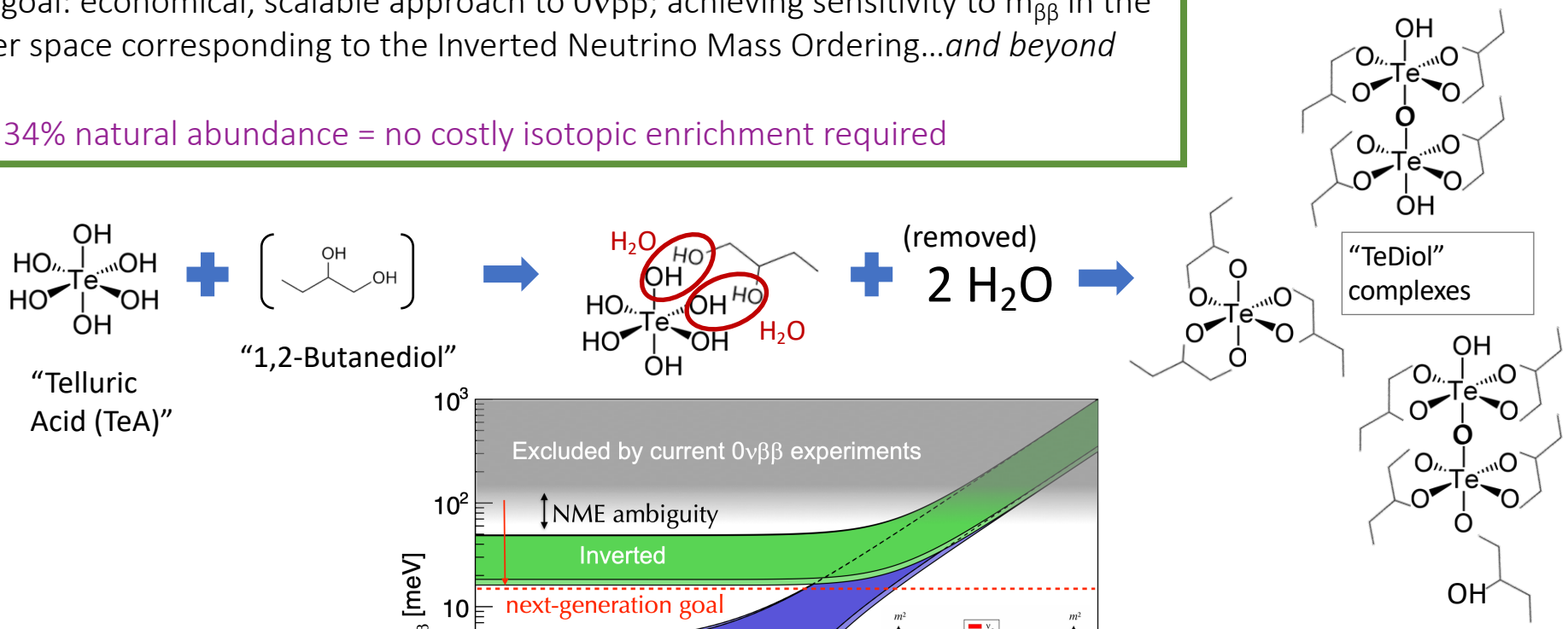
- are being demonstrated!
- SNO+ has a diverse program of neutrino (and other) physics that is being pursued.
- With the detector performing well; with all background components being measured and constrained (most coming in at or below target levels), it looks promising for the final phase of SNO+…

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 isotopic enrichment required



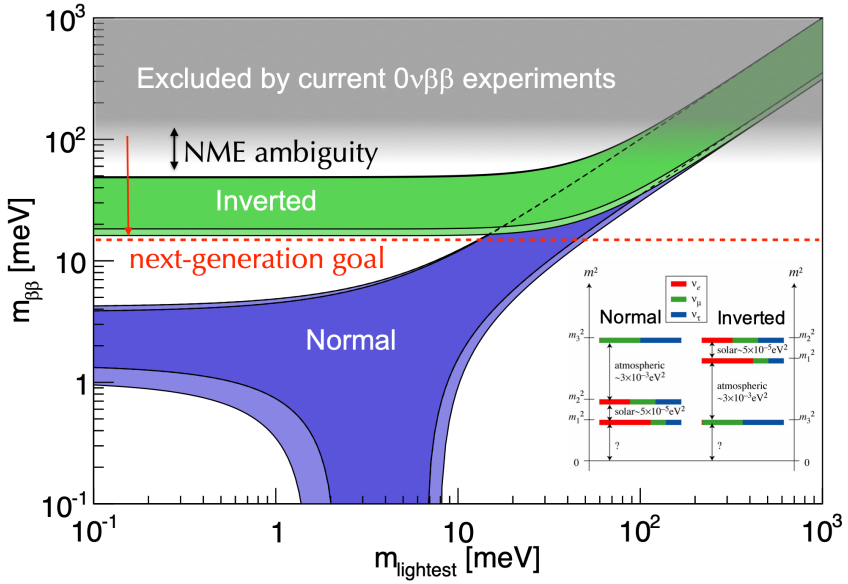
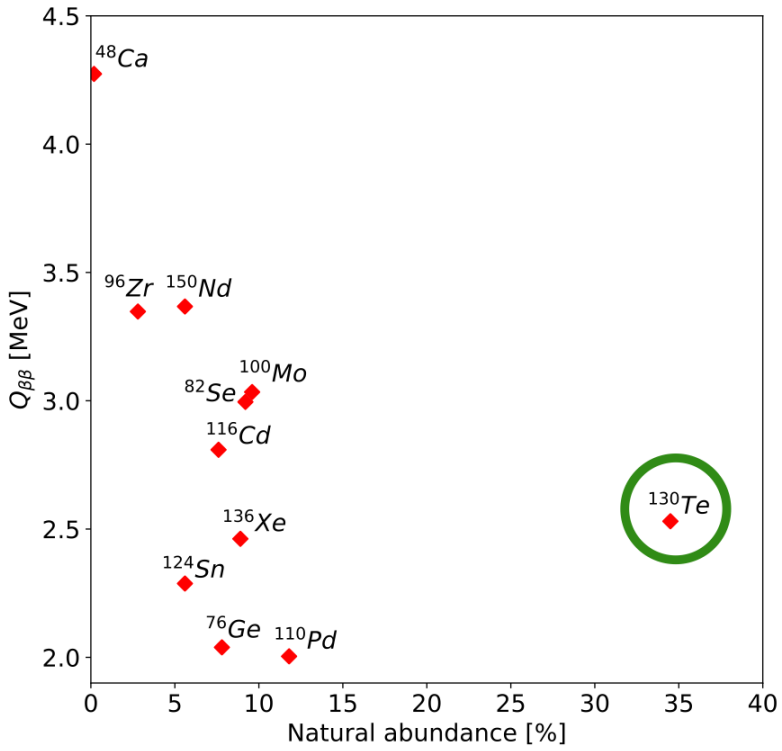
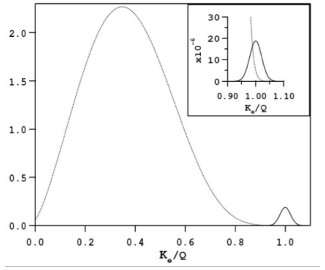


Figure from J. Detwiler talk, Neutrino 2020

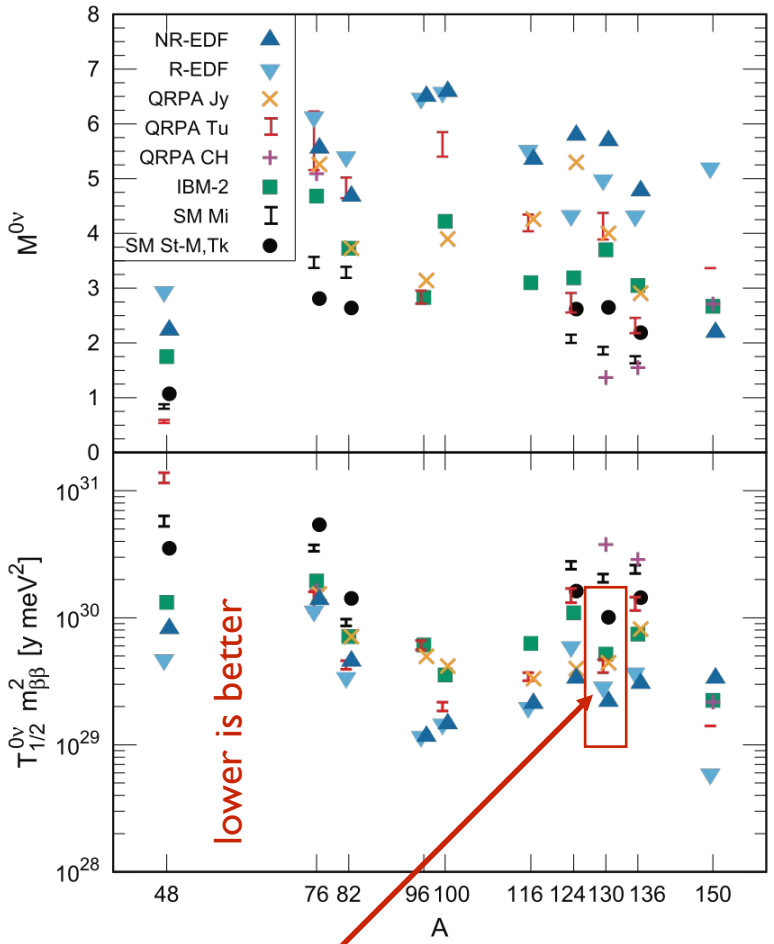
Tellurium for Double Beta Decay



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

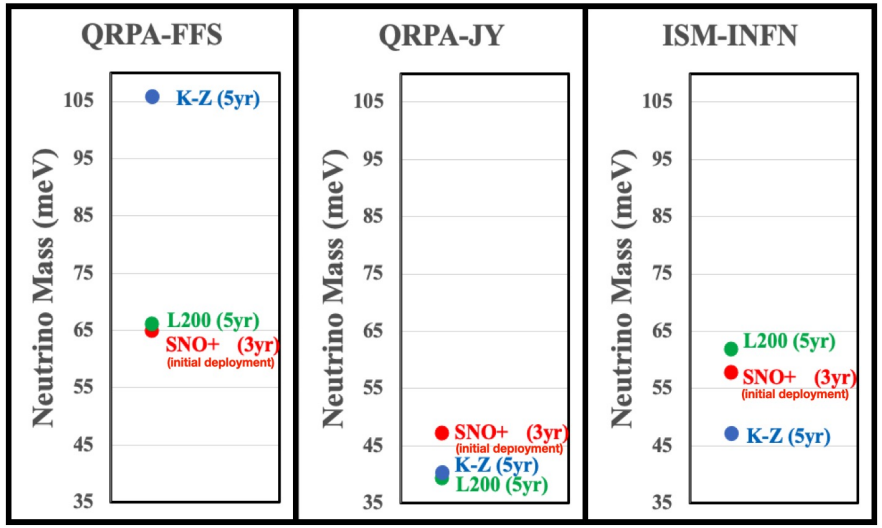
- Previous slide: “why tellurium?”
- This slide: “why in liquid scintillator?”

1. very low backgrounds: 5×10^{-7} counts/keV/$kg_{\text{fiducial detector}}$/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)

The dependence of a putative signal with amount of isotope would be a strong confirmation!

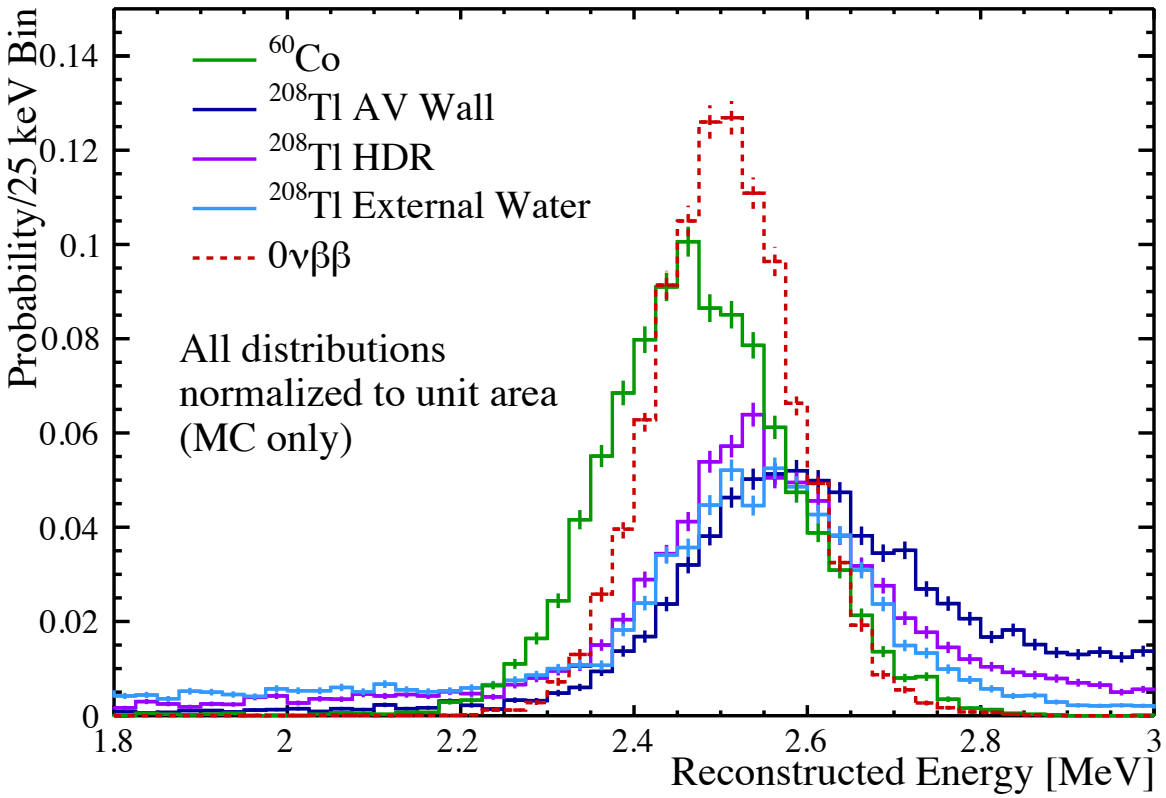
SNO+ Te DBD Additional Considerations

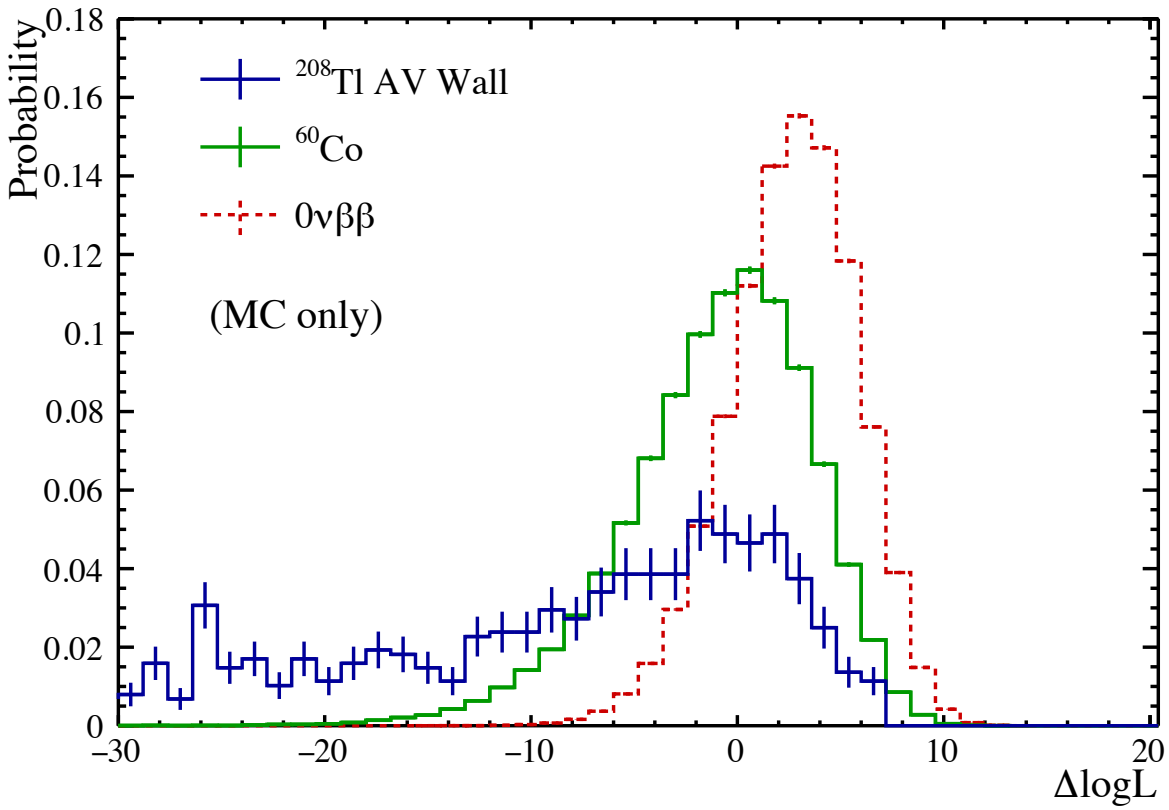
- ^{130}Te DBD is scalable, cost effective, unimpacted by geopolitical events that currently severely affect the availability of isotopic enrichment
- KL-Z 800 has world-leading sensitivity (upper limit 36-156 meV) and highlights the strength of the loaded LS DBD approach
- The competition does not make SNO+ Te DBD less relevant because of
  - complementarity of isotope; NME model dependencies
  - KL-Z limit does not exclude discovery by SNO+ with 0.5% Te
  - higher loading further extends SNO+ sensitivity and "fills the gap", before larger experiments like nEXO come online
  - initial deployment of Te would already be competitive and ready to test any hints of a positive signal
  - 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



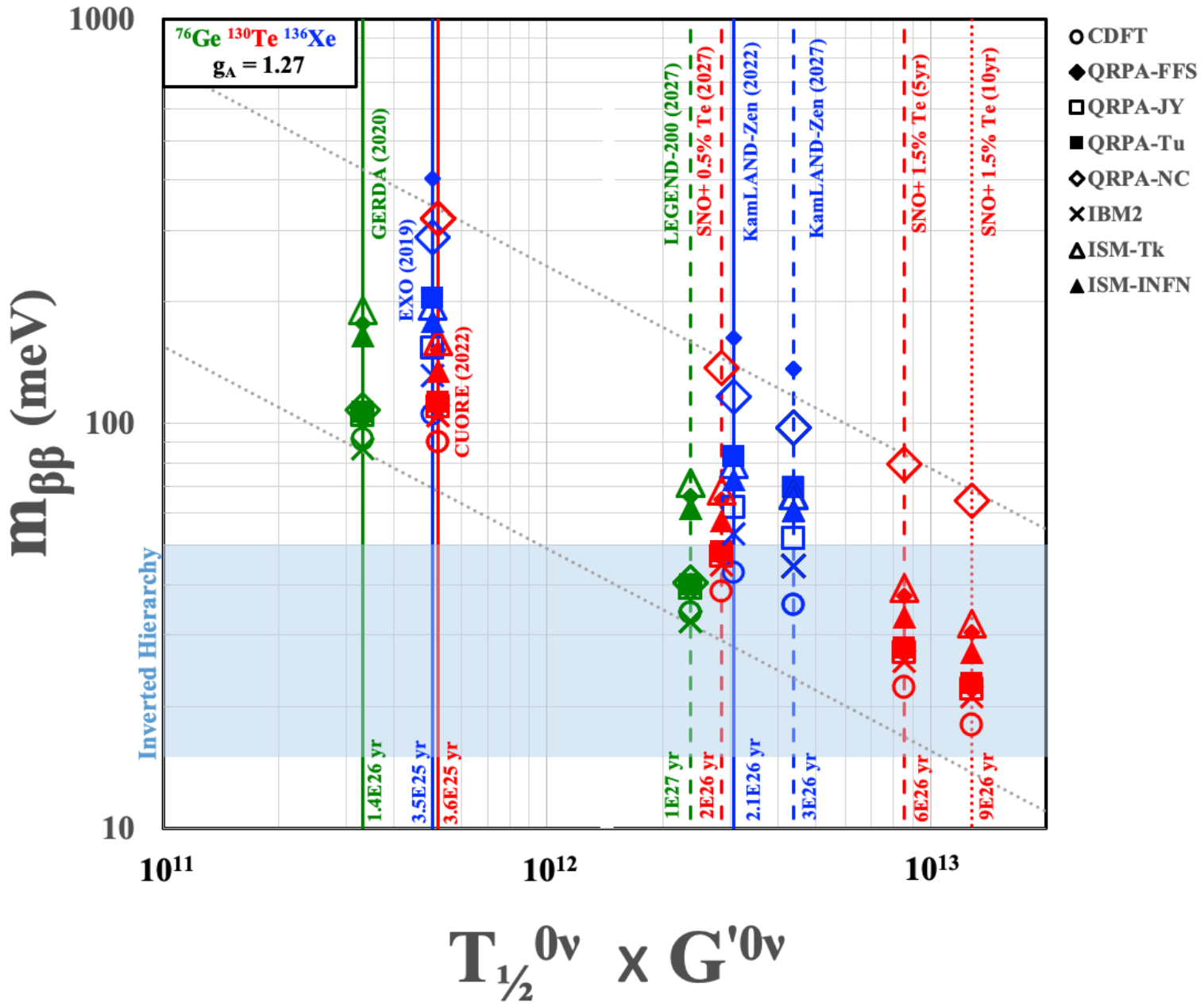
- SNO+ also has single-site/multi-site background constraining power

SNO+ Multi-site Background
Likelihood Constraint





Sensitivity



Compared to experiments that are running or completely funded and being built

Status of SNO+ Te DBD

Tellurium systems are built and ready for operation

- SNO+ is ready to pursue full-scale test batches in 2022 and 2023 to purify telluric acid and synthesize tellurium-diol, with SNOLAB assistance in this effort to help retire risks
- Following demonstration of operations and subsequent approvals, aim to begin loading Te in the detector in 2024 for the start of the double beta decay phase
- Meanwhile, the SNO+ project, with endorsement from SNOLAB, is completing R&D to establish the viability and execution plans of Te loading at the 1.5%-2.0% concentration, enabling reaching our goal of DBD sensitivity in the Inverted Mass Ordering region of parameter space

Telluric acid purification

Te-diol synthesis

CFI IF 2015 project: completed the construction of two Te plants underground between 2016-2019 (with no project extension required)

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
- 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