The SNO+ Experiment

Nuno Barros, for the SNO+ collaboration

Rencontres de Physique de La Vallée d'Aoste
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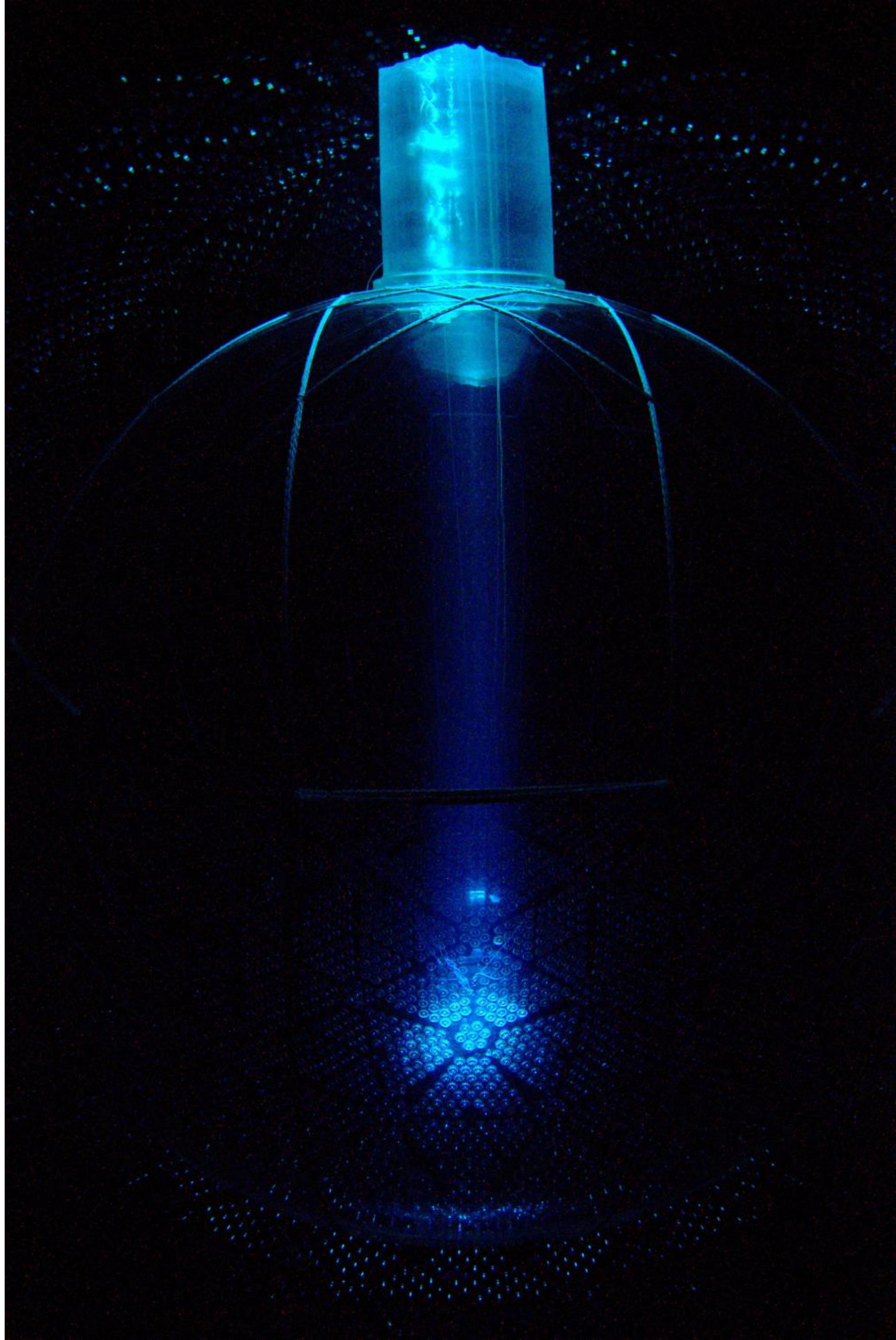
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS



The SNO+ Detector

- Multipurpose neutrino detector located at SNOLAB in Sudbury, Ontario

N_2 Cover Gas blanket

Acrylic vessel (AV)
12 m diameter
5 cm thick

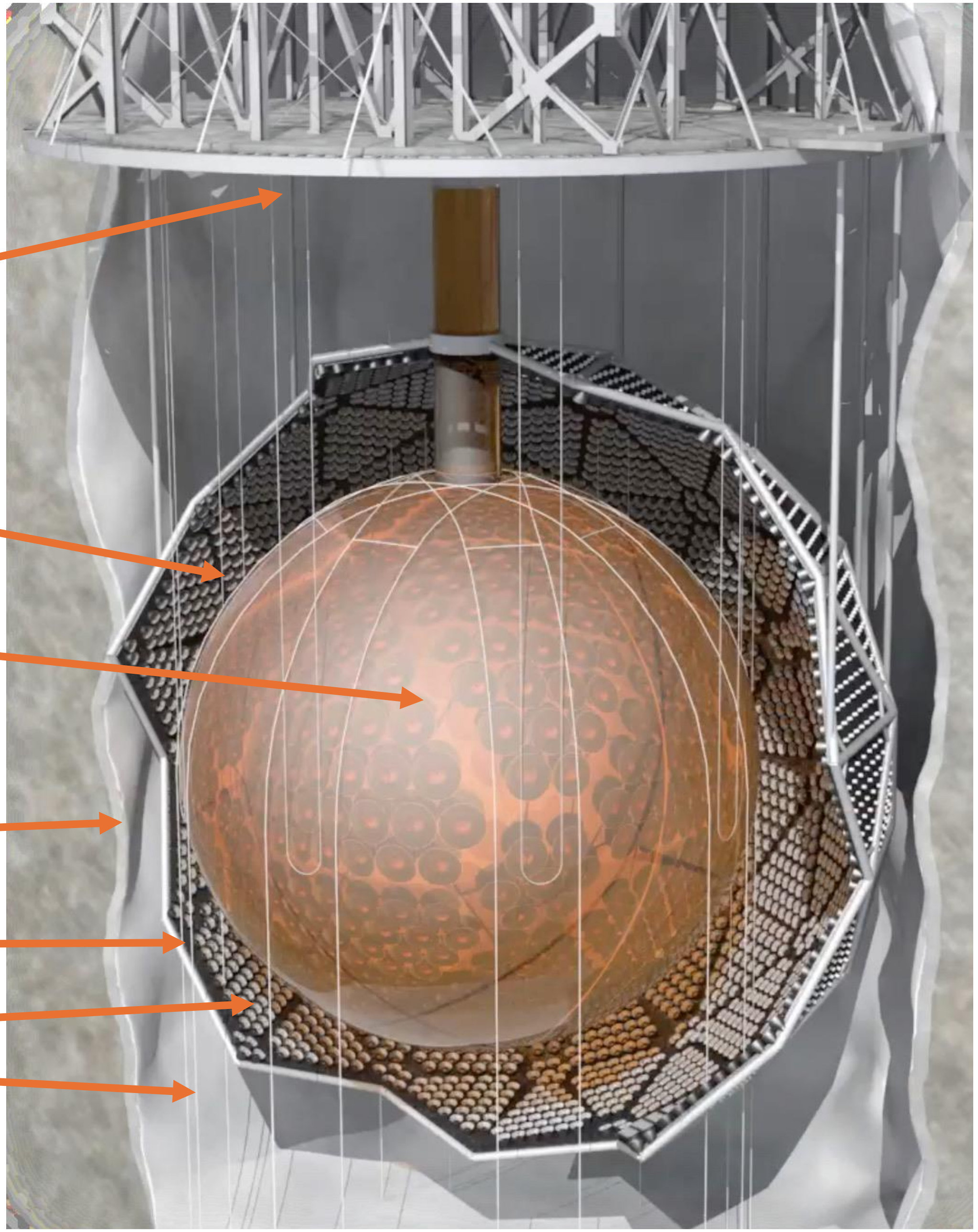
3 media (and corresponding data taking phases)
- 905 tonnes of ultra-pure water
- 780 tonnes of LAB+PPO
- Addition of 3.9 t *natTe-loaded scintillator*

Radon-impermeable plastic covering the cavity walls.

~9300 photomultiplier tubes (PMTs)

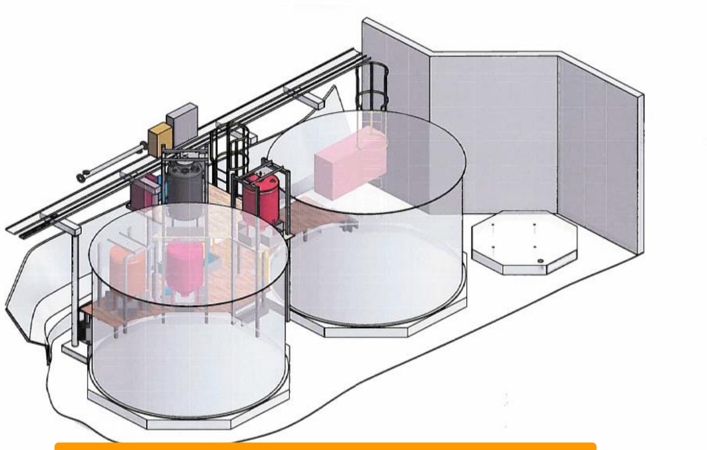
Ultra-pure water shielding

2070 m of rock overburden
- ~70 μ/day



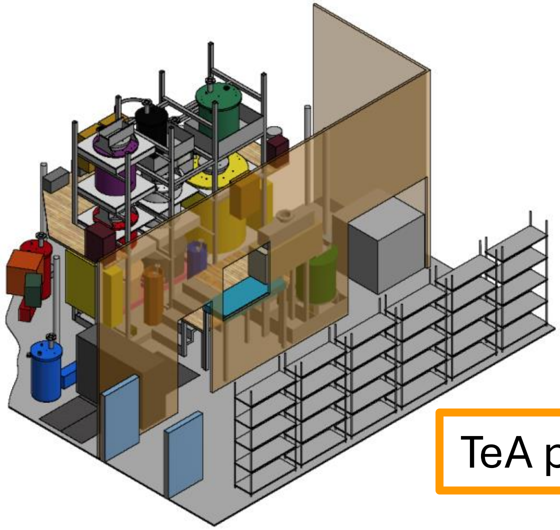
The SNO+ Detector: media purification

- Material purification is a key aspect of SNO+
- Four purification plants installed underground for water, scintillator and Te
- Can recirculate and repurify water and scintillator
- Extensive QA campaigns at each stage of theprocess:
    - before, during and after filling/loading



TeDiol purification plant

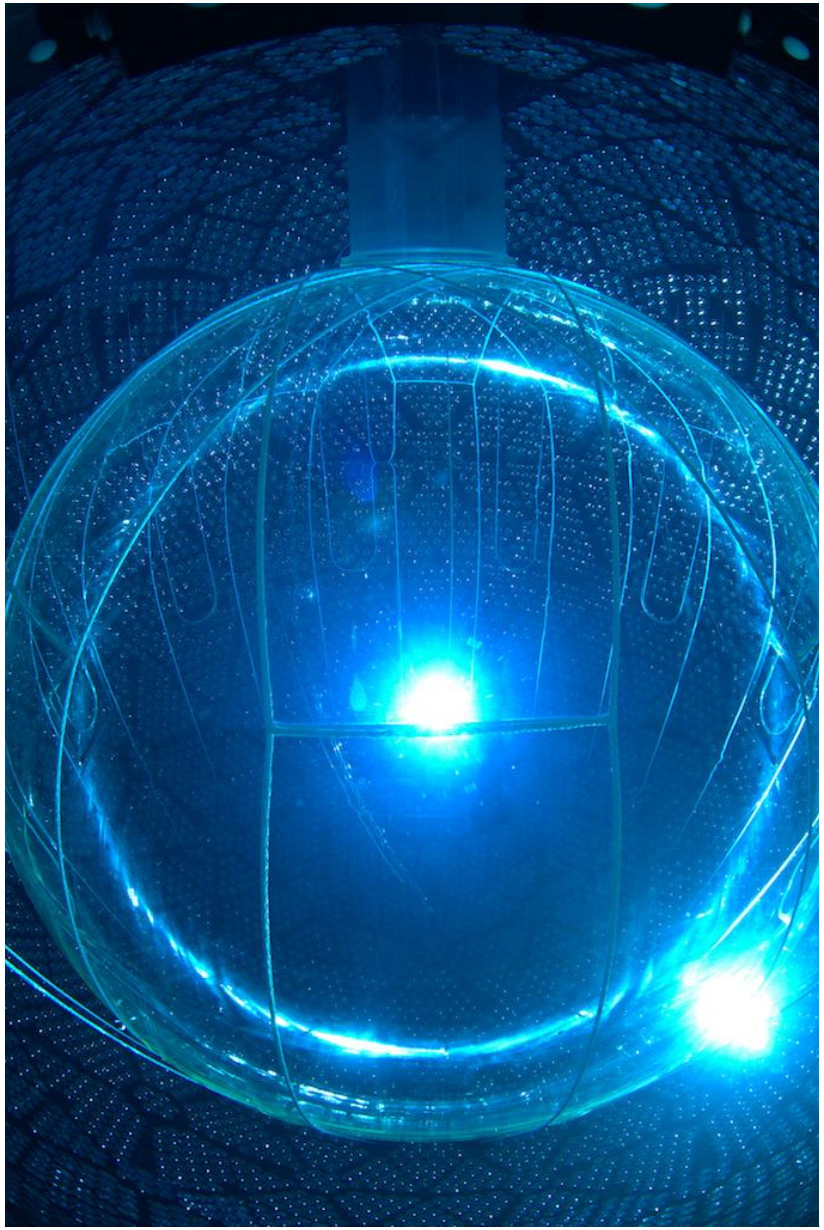
LS purification plant



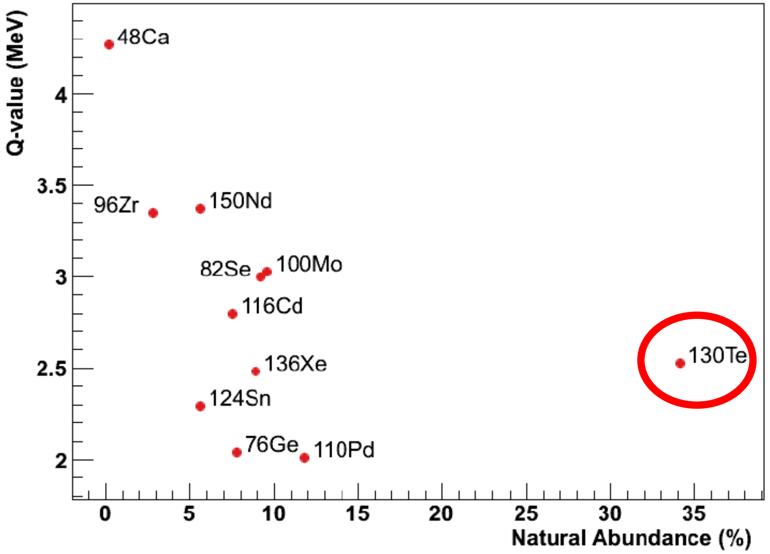
TeA purification plant

The SNO+ Detector

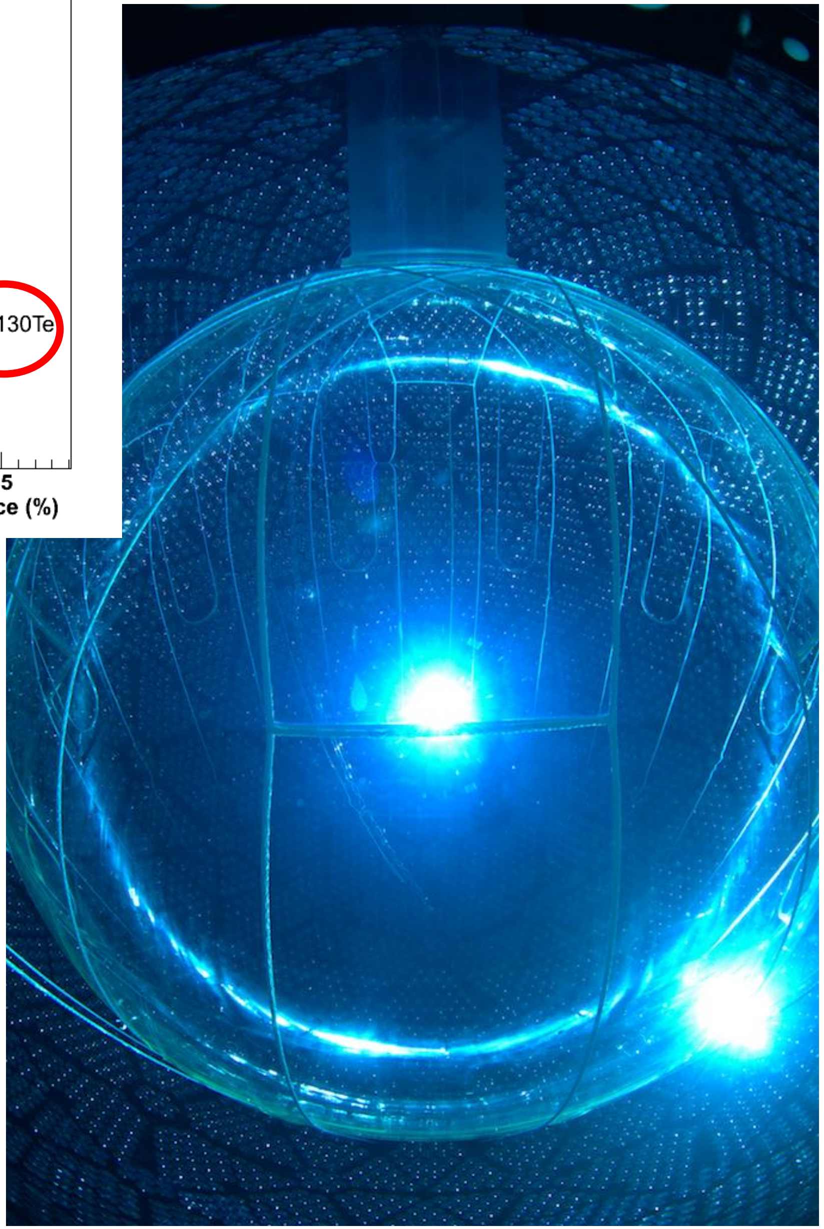
- Extensive Physics Program covering all stages of the experiment:
  - **Neutrinoless Double Beta Decay**
    - Use ^{130}Te as isotope of choice
    - Primary goal of the experiment
  - Solar Neutrinos
    - Spanning across all three phases of the experiment
    - Different energy thresholds for each phase
  - Reactor Antineutrinos
    - Spanning across all three phases of the experiment
    - Analysis of flux, spectrum and oscillation parameters
  - Geo-neutrinos
  - Supernova neutrinos
  - Other physics
    - E.g. Nucleon decay, DSNB



$0\nu\beta\beta$ with SNO+



- Major advantages of 130Te
  - No need for enrichment
  - Long $2\nu\beta\beta$ half-life ($7.9\text{x}10^{20}$ years)
  - High Q-value at 2.527 MeV



- Major advantages of SNO+
  1. Large detector
     - Rejection of external backgrounds through fiducialization
  2. Loaded liquid scintillator
     - Fast timing allows rejection of coincidence backgrounds
     - High light yield for good resolution = target 460 PMT hits /MeV
     - Loading can be scaled
  - The phased loading approach
    - Constrain and validate the detector model
    - Target-out measurement before and during Te loading

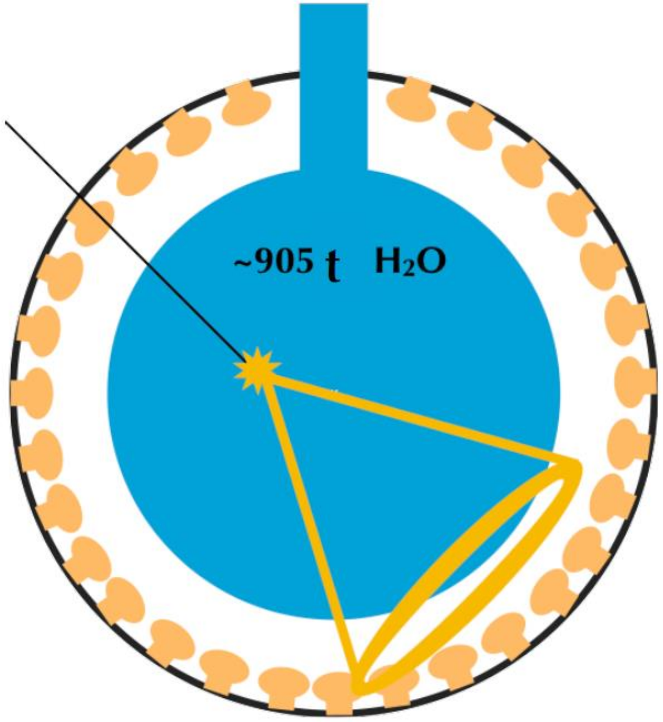
SNO+ Water Phase

2017 2018 2019 2020 2021 2022 2023

May – Dec 2017
(~115 gold physics days)
First SNO+ water phase

Oct 2018 – June 2019
(~185 gold physics days)
Second SNO+ water phase

Additional Cover gas shielding to reduce Rn ingresses in water



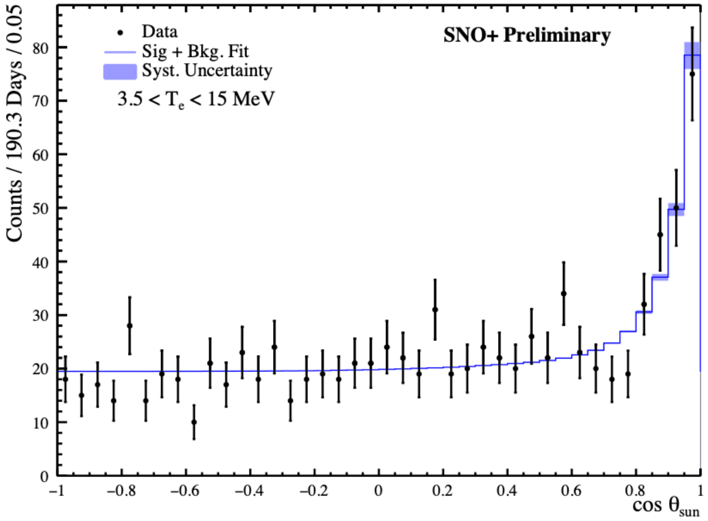
- **Major Outcomes**
  - Improved limits for invisible modes of nucleon decay
    - Phys. Rev. D 99, 032008 (2019), Phys.Rev.D 105, 112012 (2022)
  - Measurement of 8B solar neutrinos
    - Phys. Rev. D 99, 012012 (2019)
  - First measurement of reactor antineutrinos using pure water
    - Phys.Rev.Lett 130, 091801 (2023)
- **0νββ Milestones**
  - Optical calibration of the detector components (external water, acrylic, PMTs)
    - JINST 16 P10021 (2021)
  - Measurement of external backgrounds

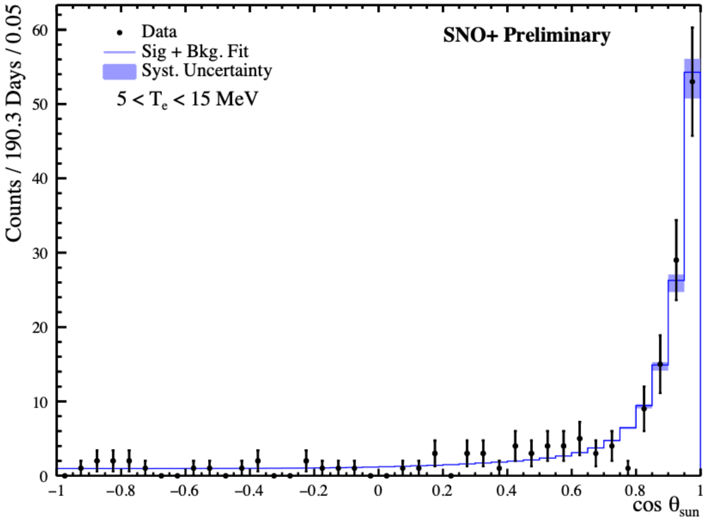
SNO+ Water Phase Physics Results

- World's best limits on invisible modes of nucleon decay
- Solar neutrinos
  - detected via neutrino-electron elastic scattering
  - now with *even lower backgrounds*
- First observation of reactor events using pure water (undoped)
  - made possible by ~50% neutron detection efficiency (highest in a water Cherenkov detector)

Best limits are from SNO+

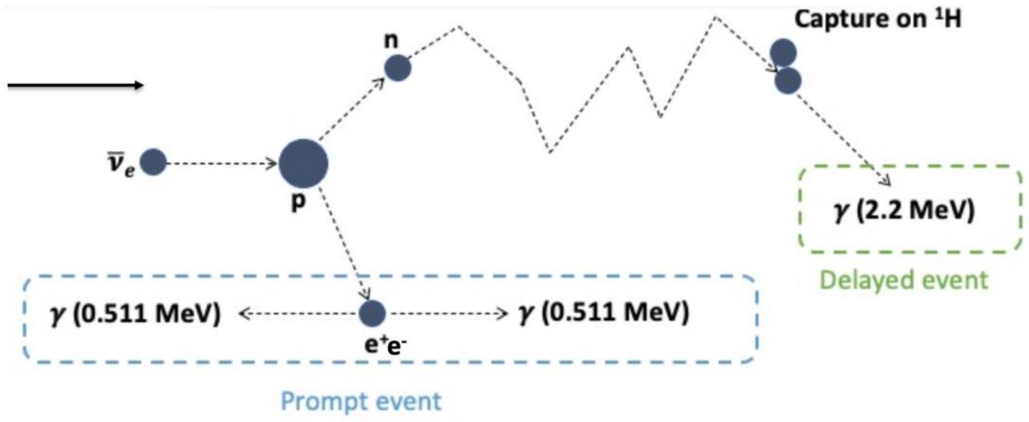
Decay Mode	Partial Lifetime Limit	Existing Limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

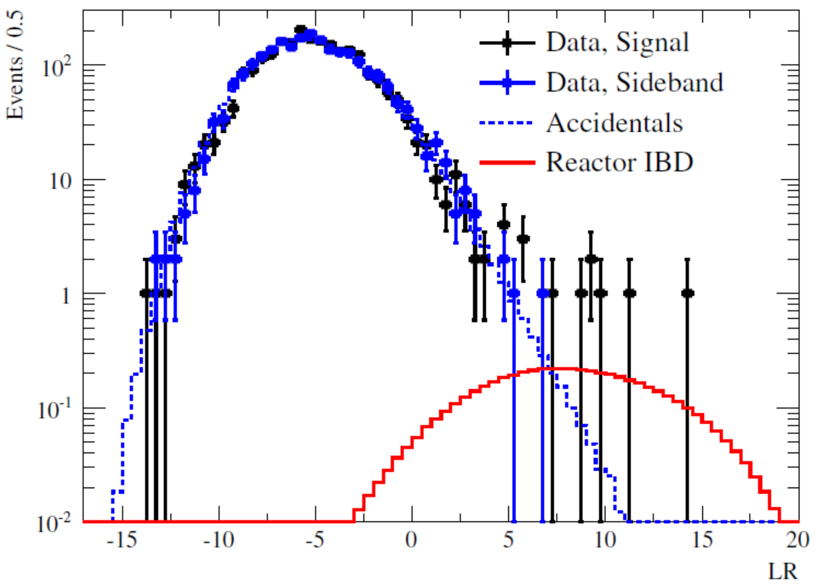


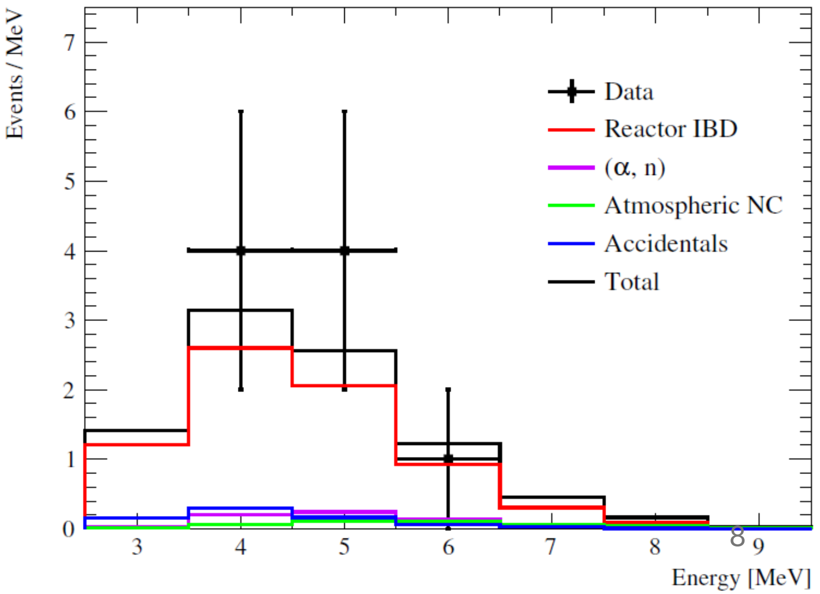


Reactor Antineutrinos in SNO+ Water Phase

- **Inverse Beta Decay (IBD)** $\bar{\nu}_e + p \rightarrow e^+ + n$





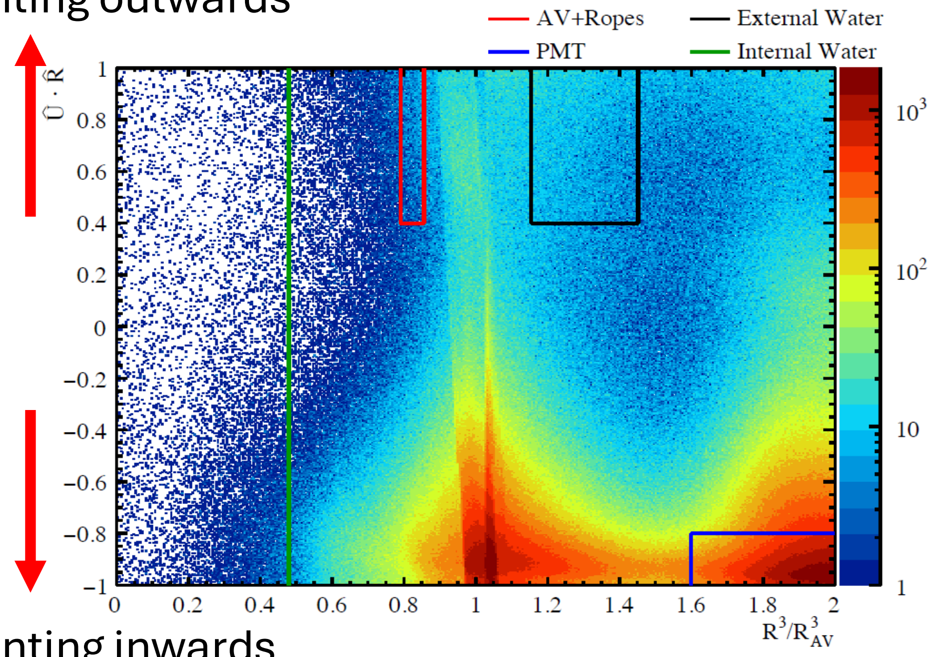


- Coincidence event
  - Prompt – positron kinetic energy (several MeV)
    - plus 1.022 MeV from annihilation γ's
  - Delayed – neutron capture 2.2 MeV γ

0νββ Milestone in Water: External Backgrounds

- Measure components that don't change with detector medium
- External background measurement during the water phase allows to use a directional cut
  - In energy: 3.0 < E < 5.0 MeV
  - In position: -5.0 < Z < 5.0 m
- Simple detector configuration

Pointing outwards



Pointing inwards

AV	$5.55 \text{ m} < R_{AV} < 5.7 \text{ m}$ $U \cdot R_{AV} > 0.4$
External Water	$6.3 \text{ m} < R < 6.8 \text{ m}$ $U \cdot R > 0.4$
PMT	$1.6 < R^3 < 2.0$ $U \cdot R < -0.8$
Internal Water	$R_{AV} < 4.7\text{m}$

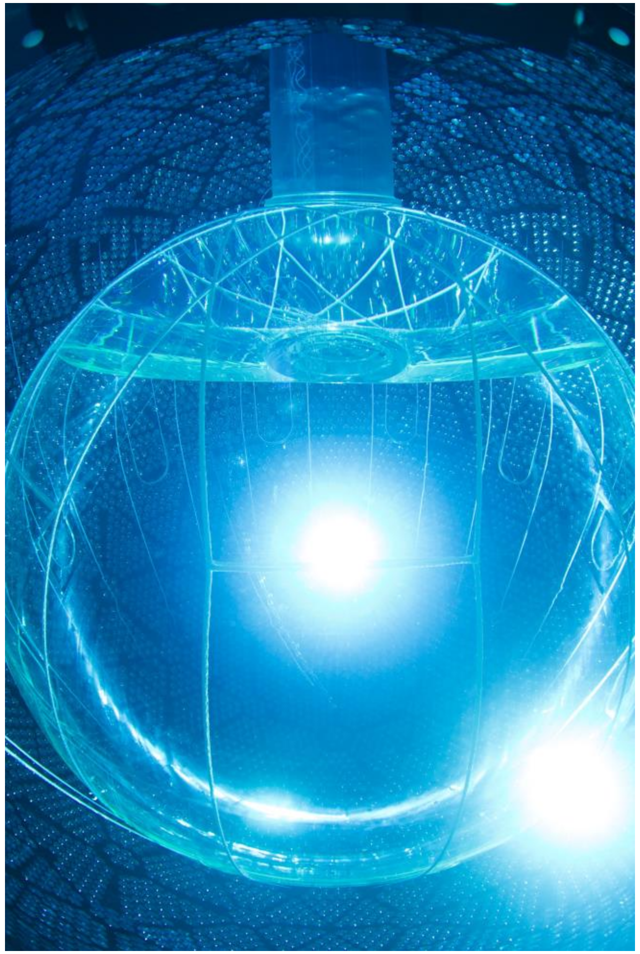
Background	Rate (Fraction of Nominal)
AV+Ropes	$0.21 \pm 0.009^{+0.64}_{-0.21}$
External Water	$0.44 \pm 0.003^{+0.32}_{-0.27}$
PMT	$1.48 \pm 0.002^{+1.65}_{-0.60}$

SNO+ Scintillator Phase

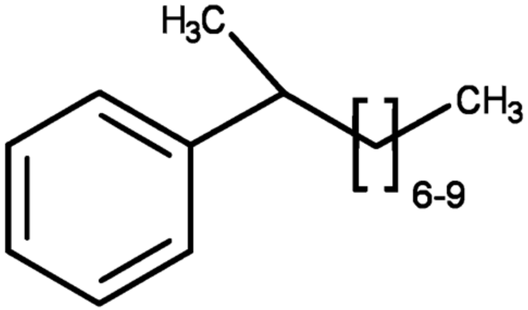
2017 2018 2019 2020 2021 2022 2023

Scintillator Fill
JINST 16 P05009

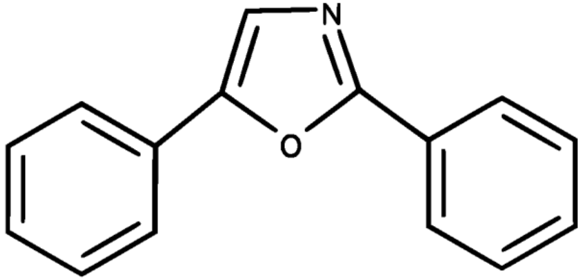
April – October 2020
(92 gold physics days)
Bonus phase: half-filled detector with 0.6 g/L PPO



- Scintillator cocktail developed by SNO+
- Allows isotopic loading

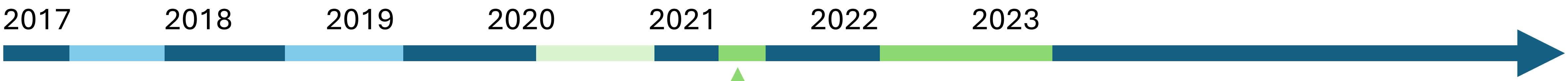


LAB: the solvent



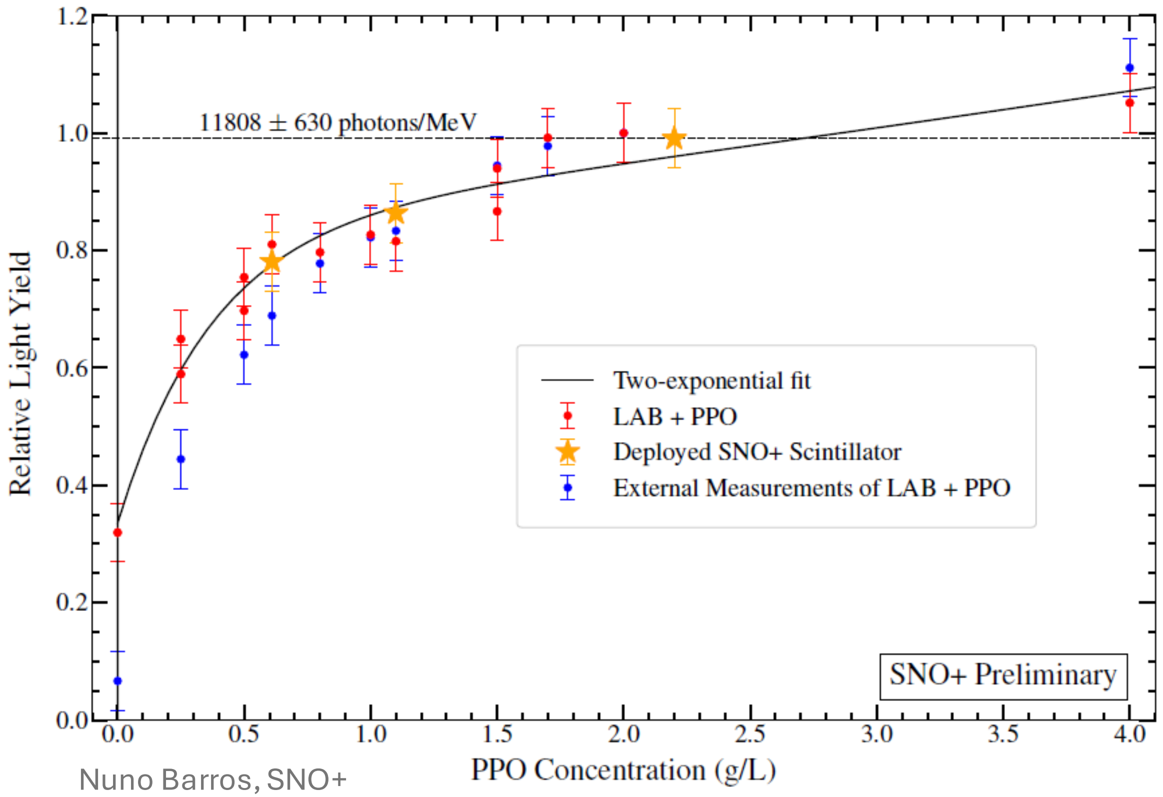
PPO: the fluor

SNO+ Scintillator Phase



April – June 2021
Bonus phase: full-filled detector with 0.6 g/L PPO)

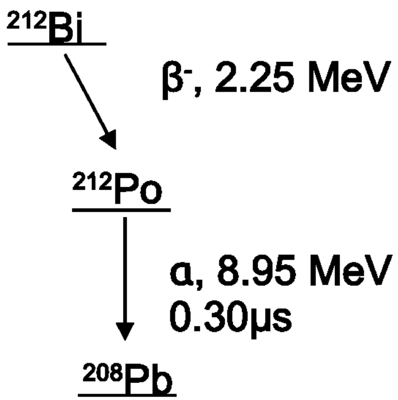
April 2022 – March 2023
Full detector with 2.2 g/L PPO



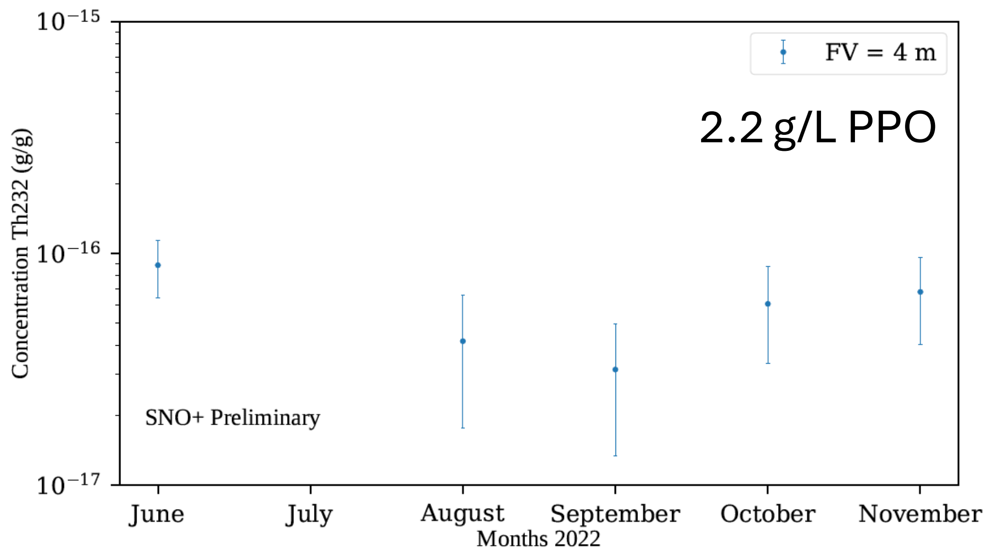
0νββ Milestone: Scintillator Backgrounds

- Monitoring internal U/Th levels

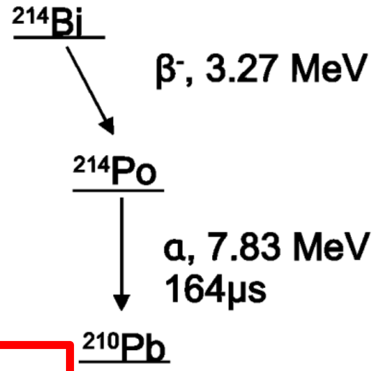
- ^{232}Th via ^{212}BiPo coincidence



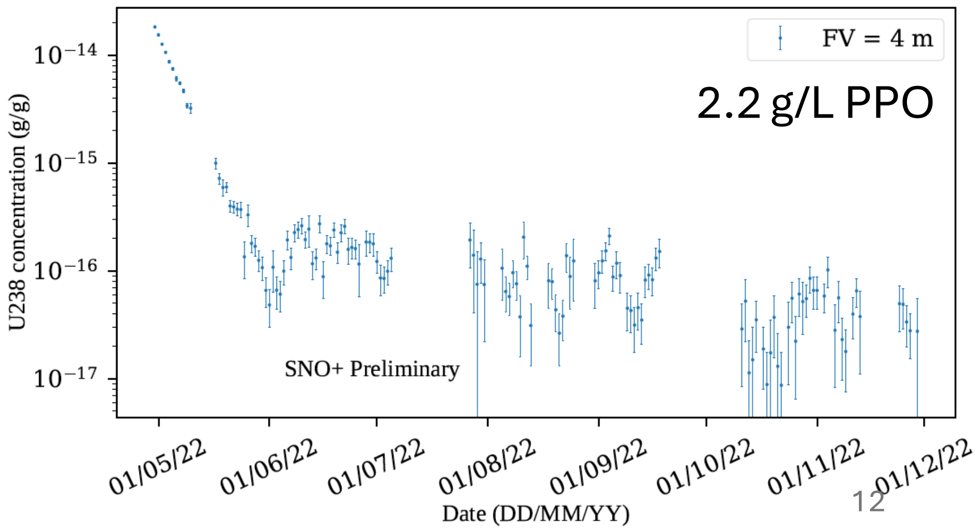
^{232}Th = (5.7±0.3)10-17 g/g



- ^{238}U via ^{214}BiPo coincidence



^{238}U = (5.3±0.1)10-17 g/g

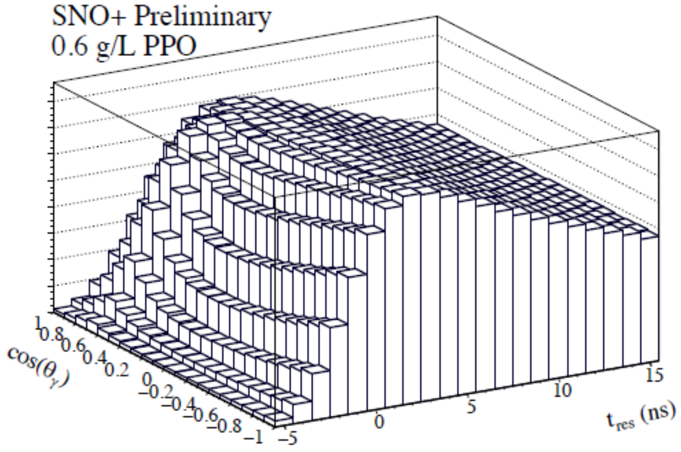


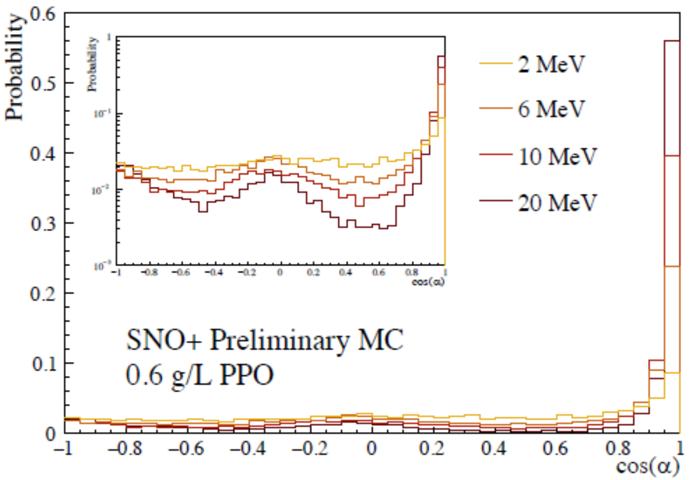
In both cases levels are below DBD requirements

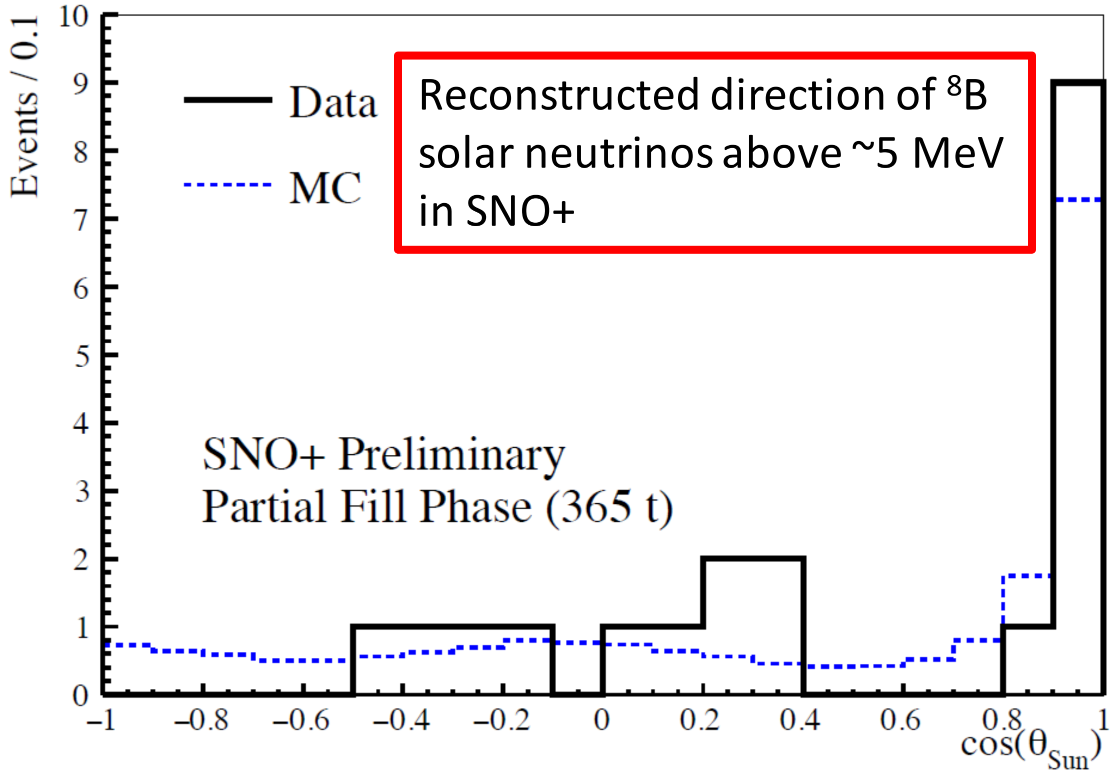
Solar directionality in scintillator

Solar neutrino direction reconstructed **event-by-event** in 0.6 g/L PPO scintillator!

- Directional Cherenkov light separated from isotropic scintillation light using timing information
- First demonstration in a high light-yield, large-scale detector







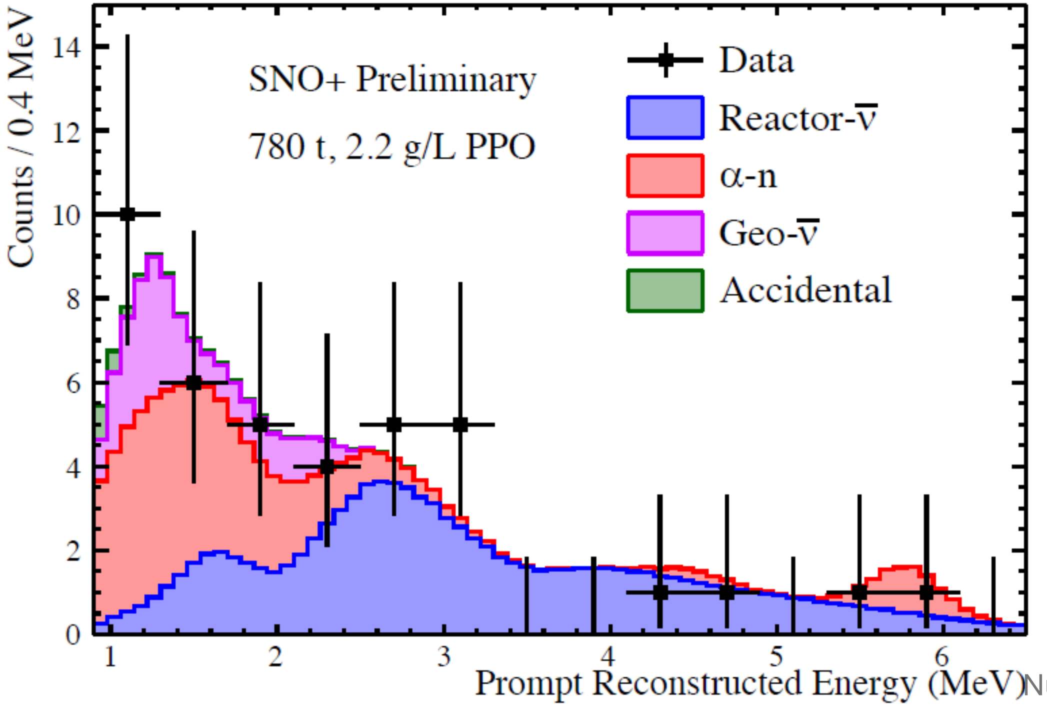
Reconstructed direction of ^{8}B solar neutrinos above ~5 MeV in SNO+

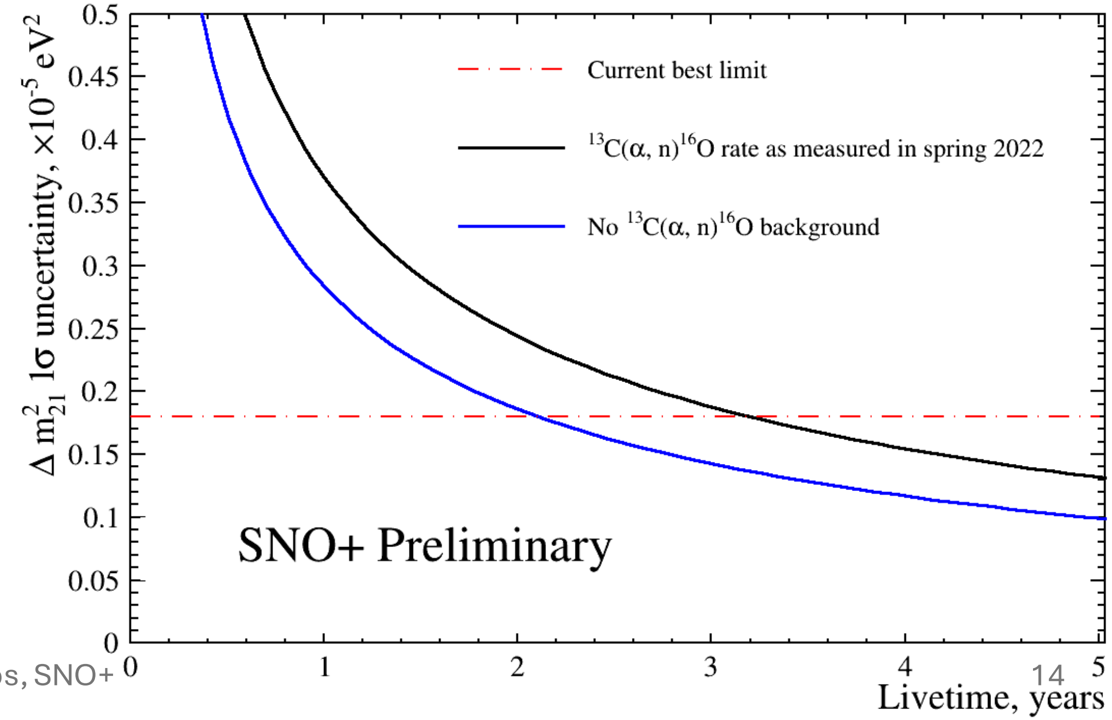
Accepted for publication in Phys. Rev. D

Antineutrinos in SNO+

On-going antineutrino analysis in scintillator

- $(\boldsymbol{\alpha}$,n) reactions are main background
- Major source of α - ^{210}Po - factor ~3 smaller from partial fill to 2.2 g/L full fill phase
- Classifier developed in-house helps separate ^{13}C($\boldsymbol{\alpha}$,n) reactions from anti-neutrinos
- Expect sensitivity to Δm_{21}^2 and geo-neutrino measurement





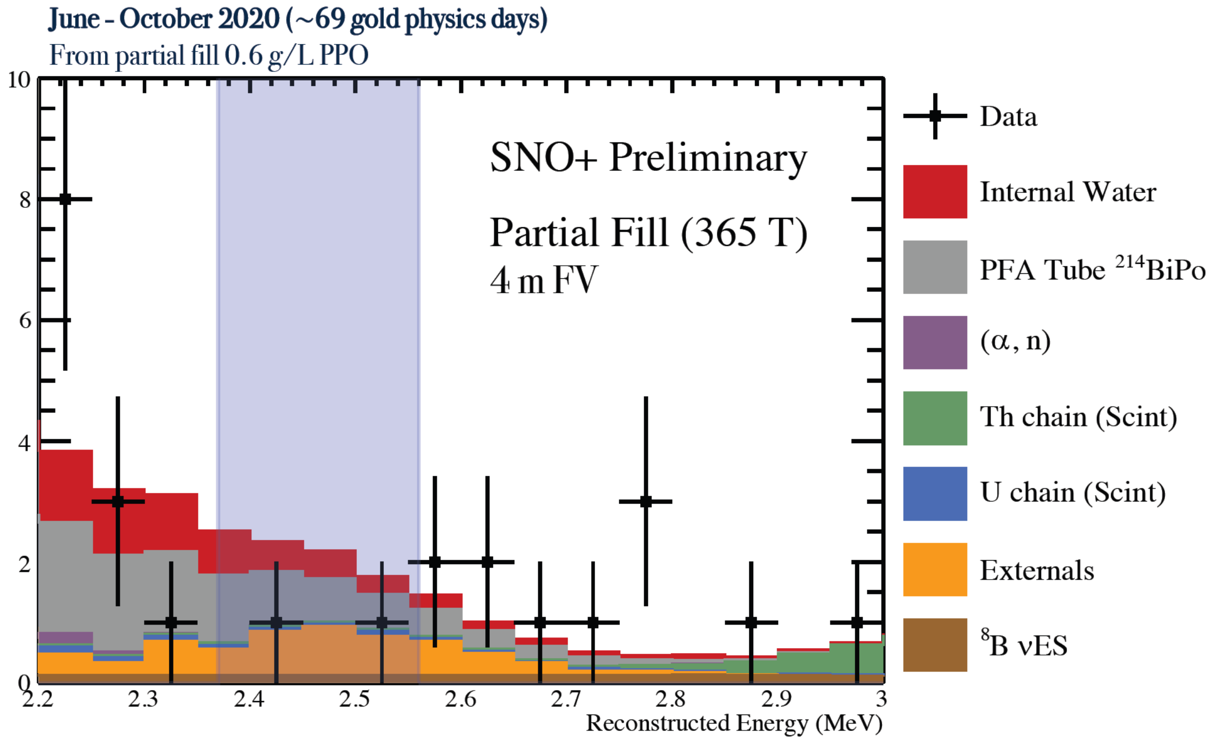
Target-Out Measurement

Preparation for the double-beta decay phase: background and target-out measurement

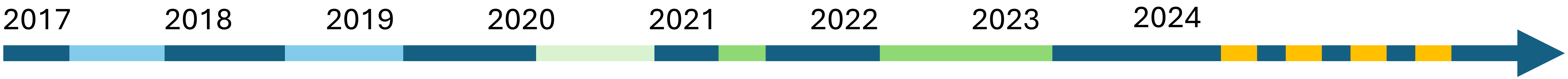
- Prepare/test analysis and techniques using real data
- Determine the count rate in the ROI in the absence of Te

- In partial-fill:
  - Expected 8 events in ROI
  - Observed 2

- In full-fill:
  - Analysis still in progress



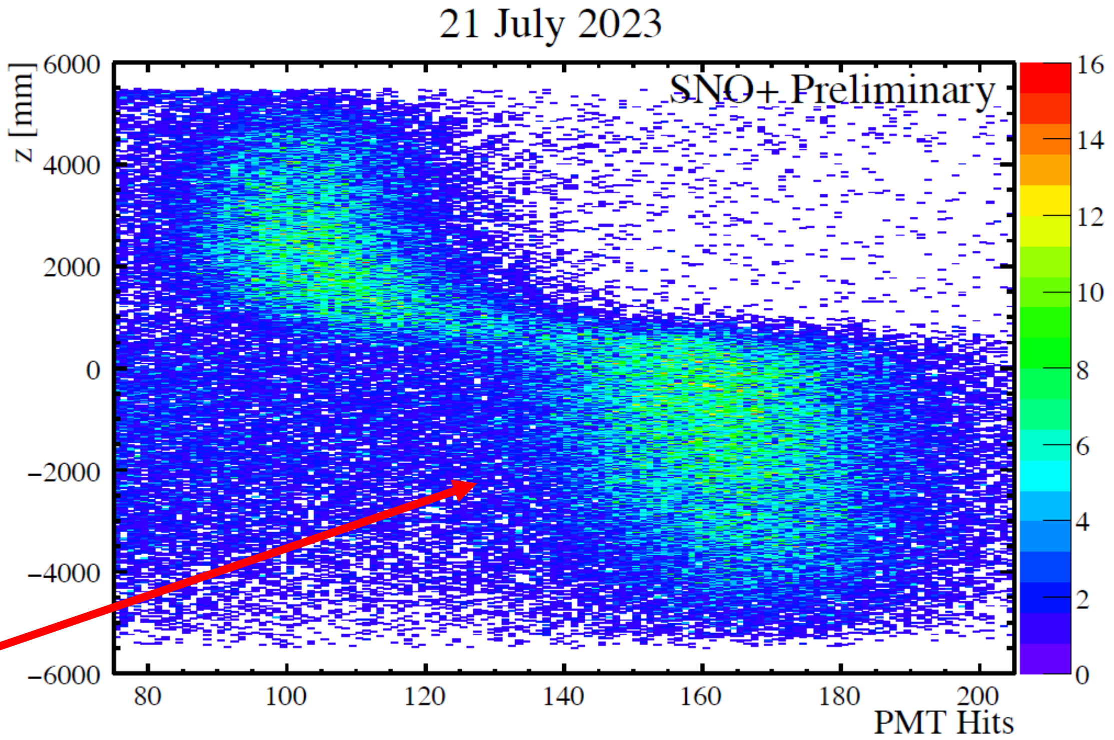
Preparing for Te-loading : Adding BisMSB



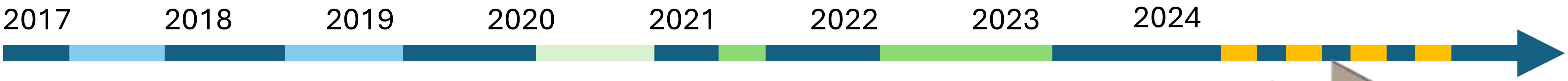
July 2023
Started to add bisMSB to the detector

- Tracking ^{210}Po decays in scintillator
- Bis-MSB added at the bottom of the detector (0.5 kg) and started to mix
- **Clear improvement (~1.5x) in light output**

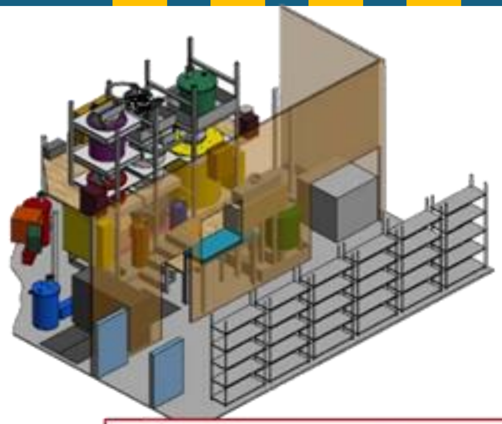
^{210}Po events in detector versus z position after adding ~0.5 mg/L bis-MSB to the bottom of the detector



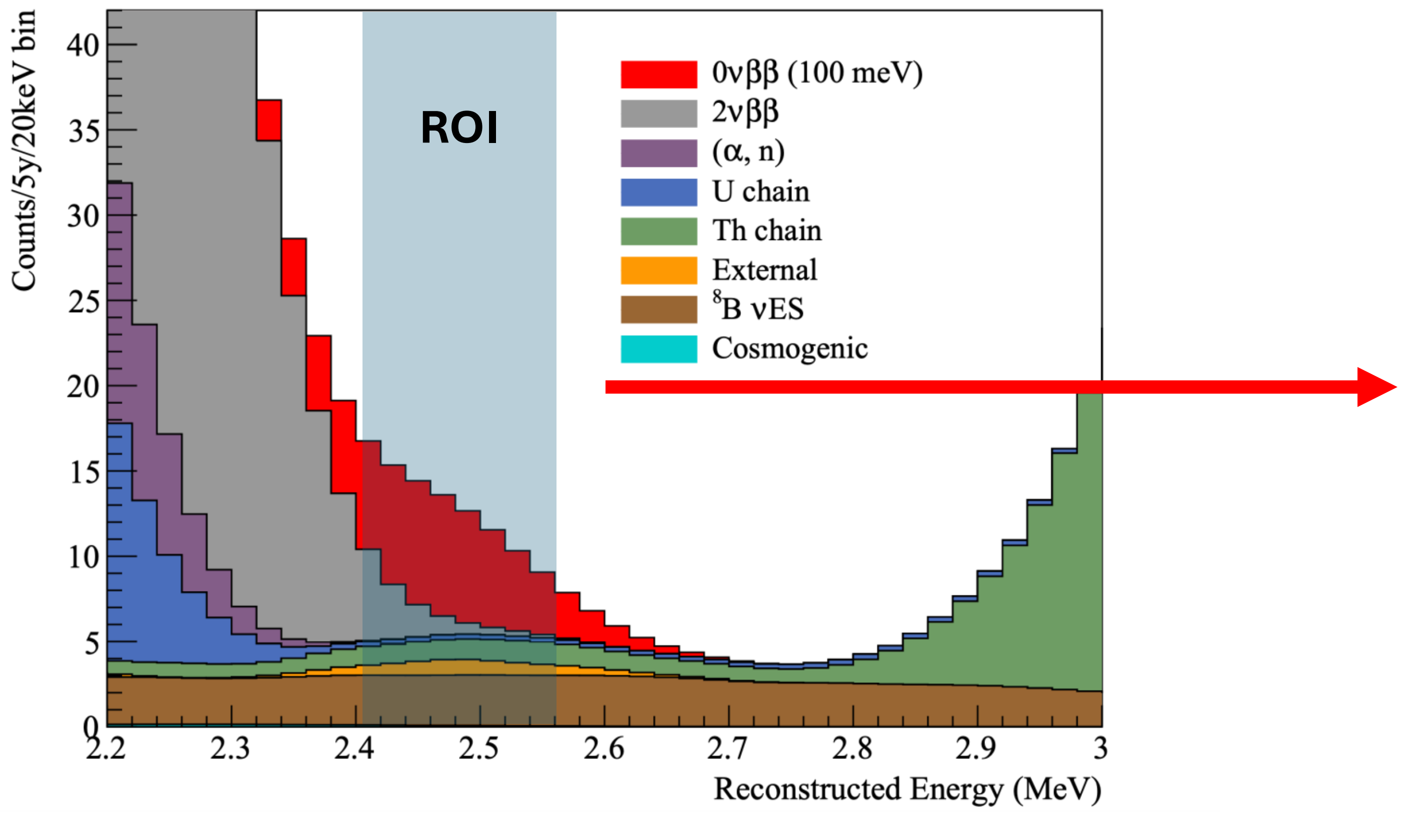
Preparing for Te-loading : Upcoming Milestones



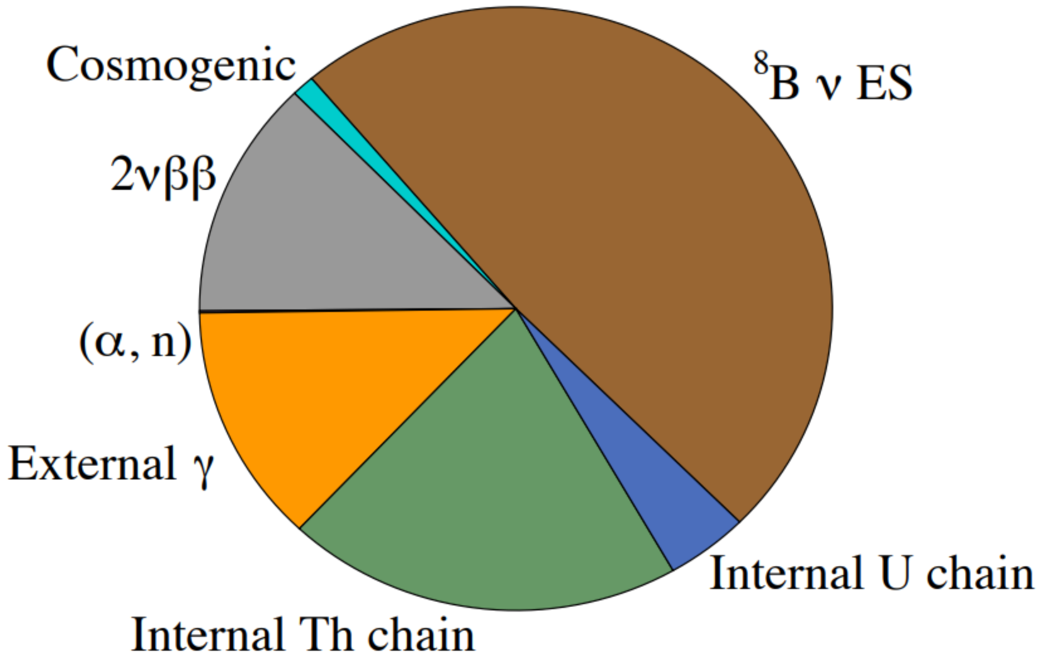
- **Major milestones:**
  - July 2023 : BisMSB added to the scintillator
  - Spring 2024 : test batch (~200 kg) of the TeA purification plant
    - First full-scale test of the SNO+ Te purification and loading systems
    - Samples will be collected for off-site ICP-MS analysis of U/Th
  - During 2024: Start adding TeLS components
  - From 2025: Start counting with Te



SNO+ Prospects: Signal / background



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



- Events in the Region Of Interest + Fiducial Volume
  - 9.47 events/yr (at nominal backgrounds)

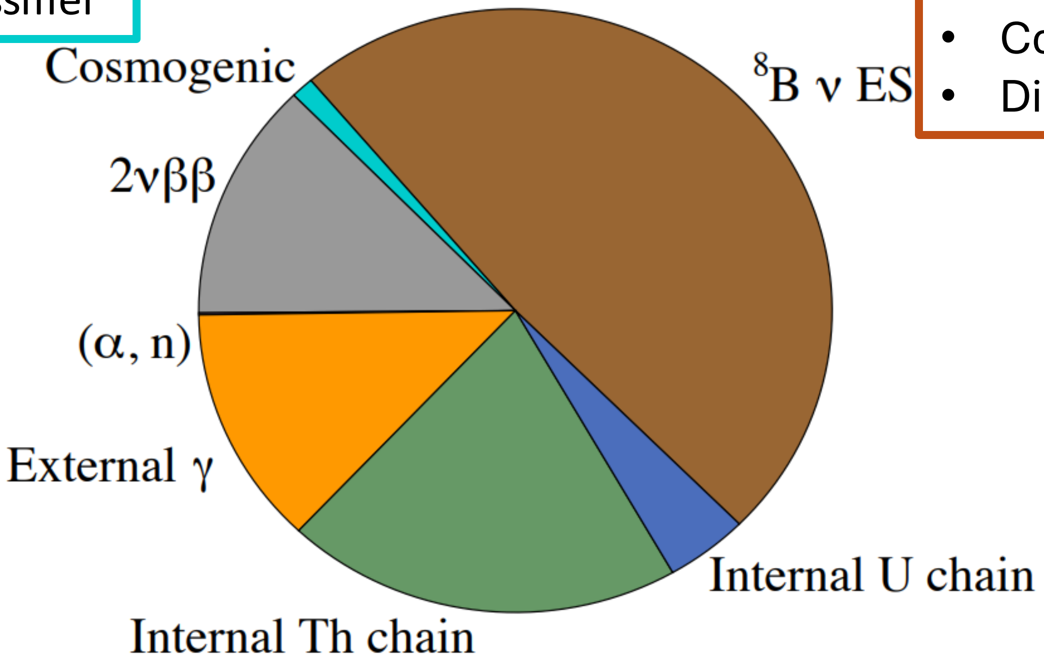
SNO+ Prospects: Background Mitigation Strategies

Cosmogenic: ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- mitigation: purification + "cool-down" UG
- First Te UG since 2015
- Can also be verified with multi-site classifier

$0\nu\beta\beta$:
- **Suppressed by asymmetric ROI**

(α,n):
- alpha-capture on ^{13}C (^{18}O)
- **Measured the contribution from LS components before Te loading**
- delayed coincidence tagging

External gammas:
- from AV, ropes, water, PMTs, mainly 208Tl
- **Measured in water phase, below nominal values**
- Fiducialization to minimize the leak in ROI

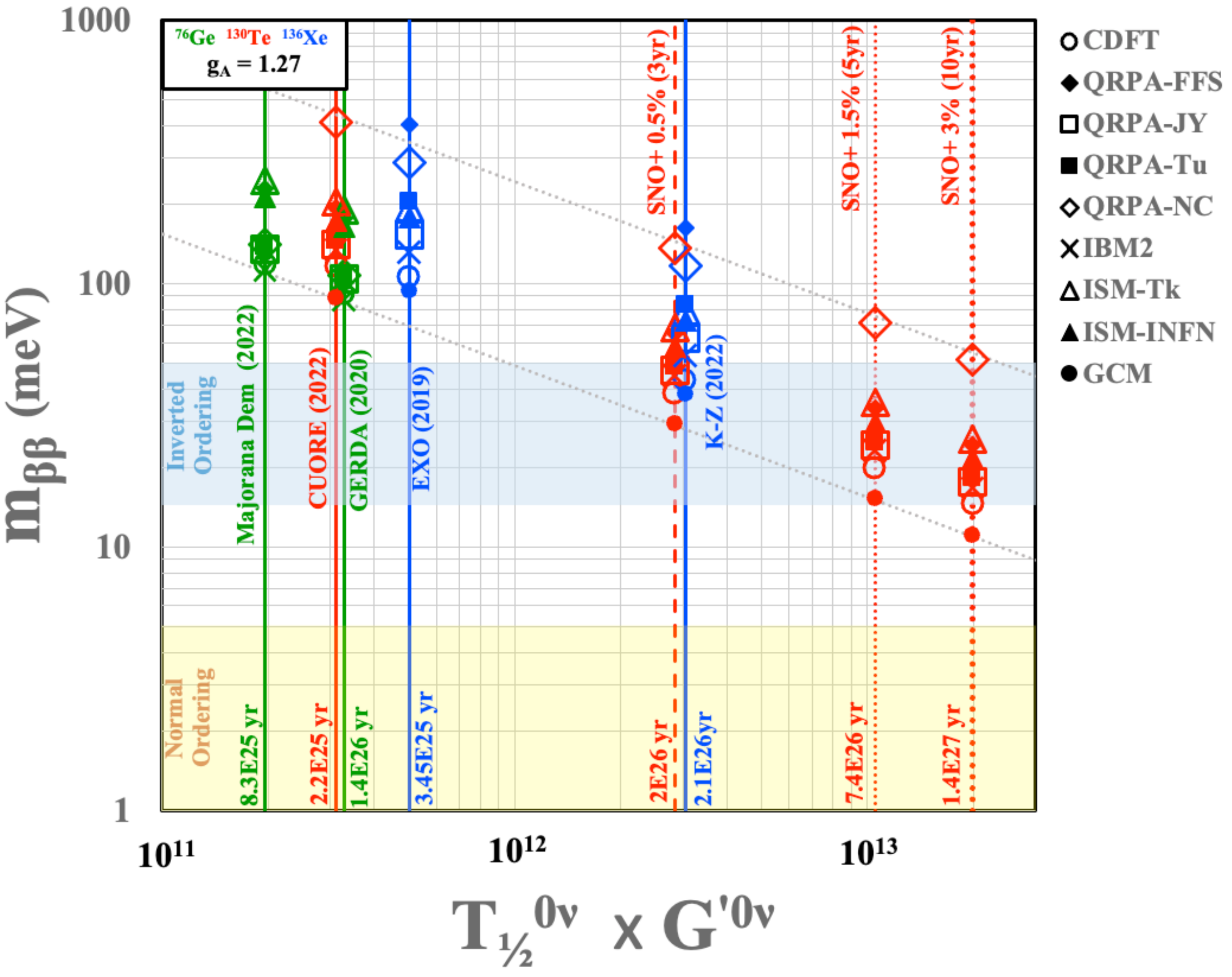


^{8}B solar neutrinos:
- Constrained by SNO/SK data
- Directionality (possibly)

Internal U/Th chain: ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- 214BiPo, 212BiPo, 210Tl
- LAB components below requirements for the TeLS phase
- Monitoring the contribution from the scintillator when adding Te

SNO+ Prospects: Sensitivity Projections

- Expected sensitivity of 2×10^{26} years
  - After 3 years
  - With 0.5% natTe loading
- Planned future higher loadings
  - Potential to cover the whole inverted ordering band
  - R&D shows good optical properties and long-term stability



Summary

- SNO+ has successfully completed its scintillator loading and is taking data with 2.2 g/L PPO as of April 2022
  - On-going addition of bisMSB in preparation for Te phase

- Much work has happened in preparation for the $0\nu\beta\beta$ searches:
  - Constant monitoring of the scintillator
  - Initial measurements show radioactive backgrounds below the targeted values

- Many exciting physics analyses on-going with scintillator data!


SNO+ 2023
EXIT
Physics