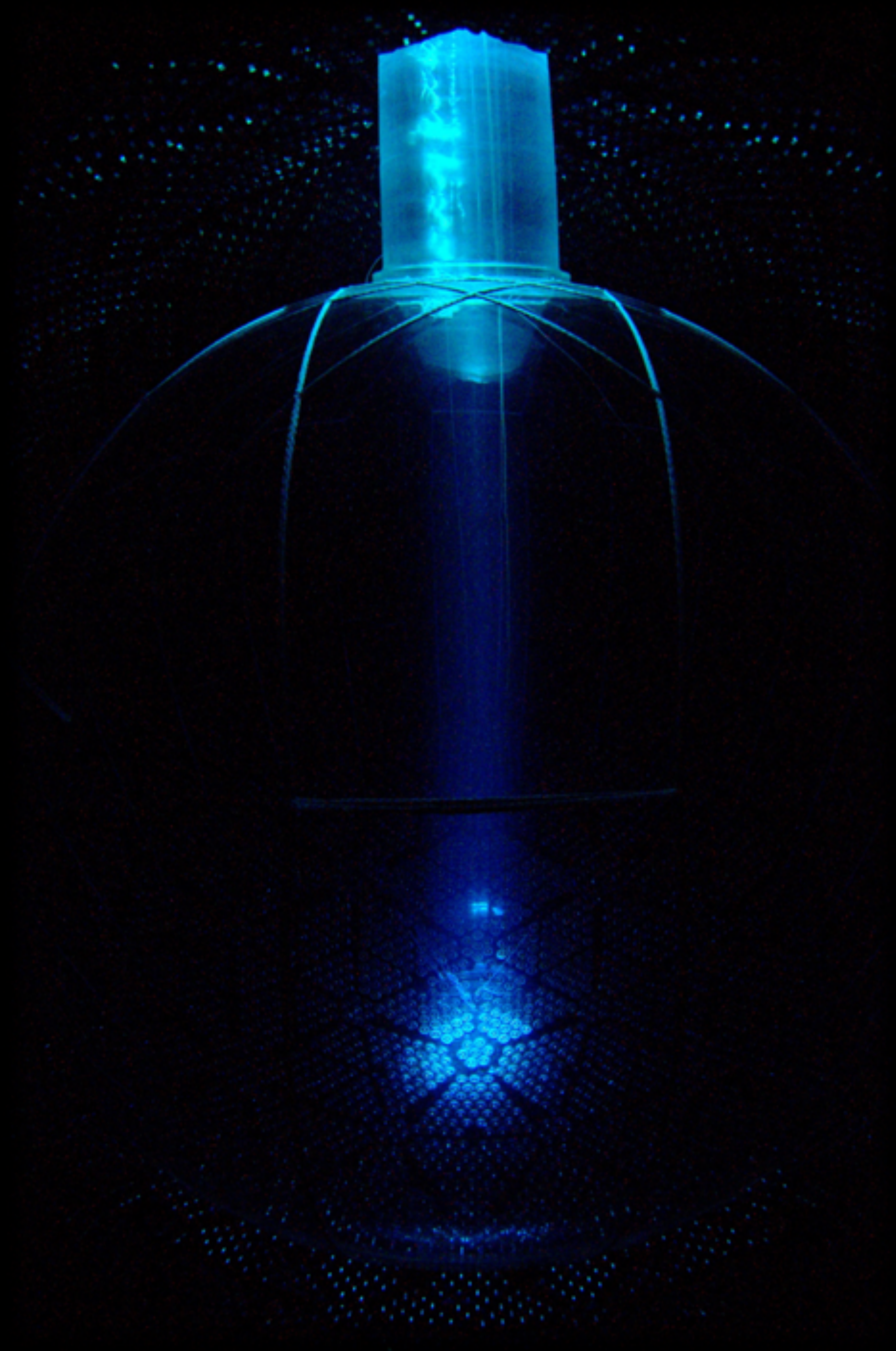

6th IDPASC /LIP PhD Student Workshop
25-27 June 2020

SNO+

Measurement of Te130 Two-Neutrino Double Beta Decay Half-life with the SNO+ Experiment:
Analysis during the Partial Fill

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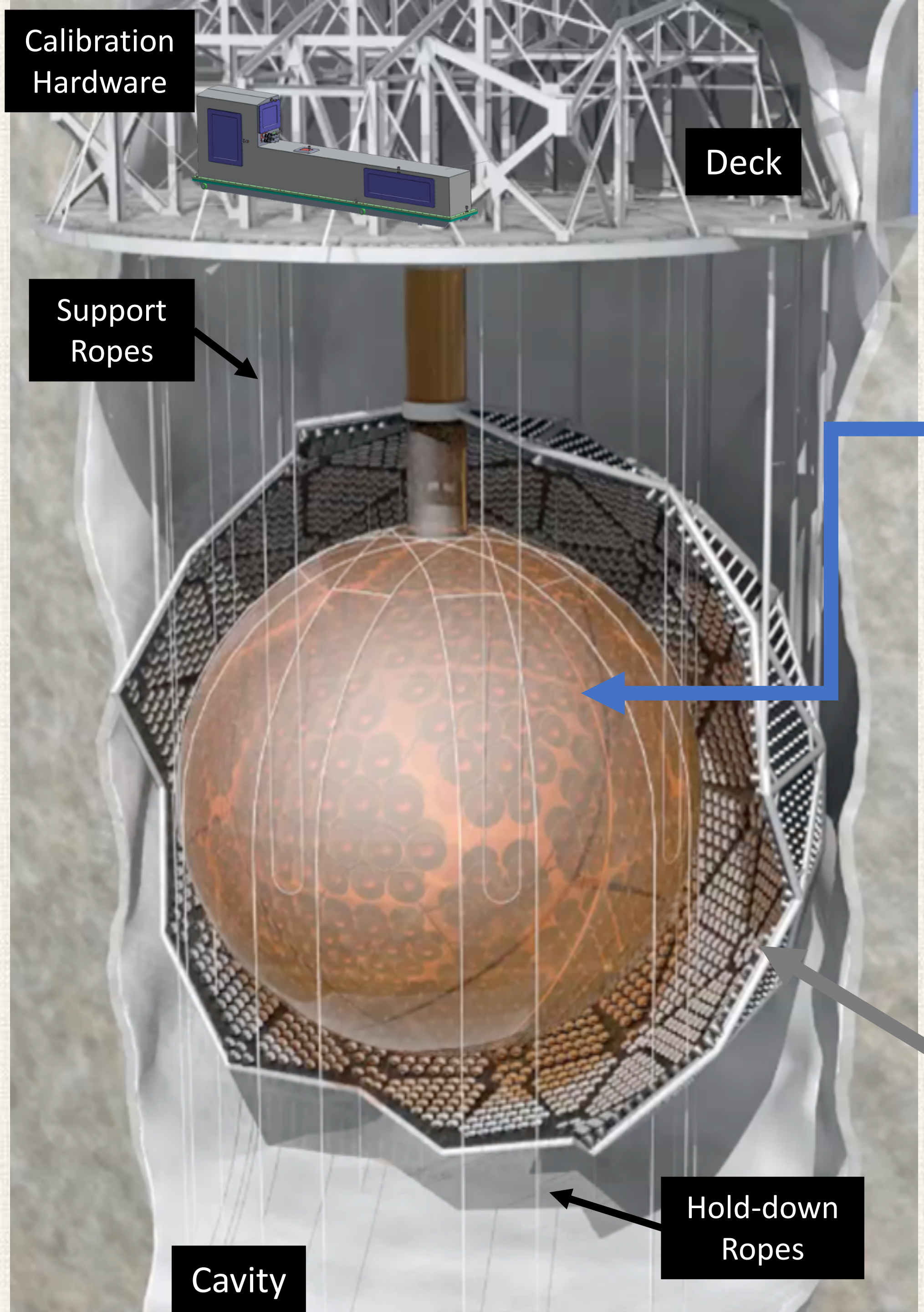
LIP Ciências ULisboa FCT Fundação para a Ciência e a Tecnologia IDPASC



The SNO+ Detector

SNOLAB, Canada, at a depth of 2km
(rock, ~5900 mwe, ~63 cosmic muons/day)

Acrylic Vessel (AV)
6 m radius, 5 cm thickness

905 tonnes of ultra-pure water

↓

780 tonnes of Liquid Scintillator

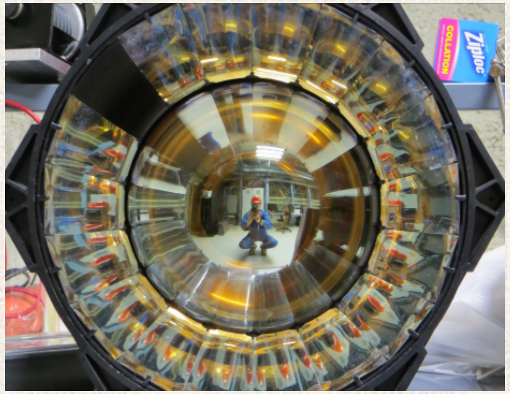
Currently almost ½ full
(365 tonnes)
Continuous Data Taking

↓

+ 3.9 tonnes of natural Tellurium

Search for ^{130}Te 0νββ-decay

PMT Support Structure (PSUP)
8.9 m radius
Holds 9400 PMTs + Concentrators



SNO+ Physics Goals

1. Water phase (Data taking 05/2017 – 07/2019)
   - Detector calibration
   - Background measurements
   - **Nucleon decay searches**
   - **^{8}B solar neutrino flux**

2. Scintillator phase (fill ongoing)
   - Background measurements
   - **Low energy solar neutrinos**
   - **Geo and reactor antineutrinos**

   Continuous data taking!

3. Tellurium phase (planned for 2020)
   - **2νββ decay lifetime of ^{130}Te**
   - **0νββ decay search with ^{130}Te**
   - **Geo and reactor antineutrinos**

- **Supernova neutrinos in all phases!**

Crucial to verify that the scintillator purity requirements are met

Analysis of Partial Fill data

$\beta\beta$-Decay of ^{130}Te

0νββ-Decay: Most promising way to prove the Majorana nature of neutrinos. Implies lepton number violation.

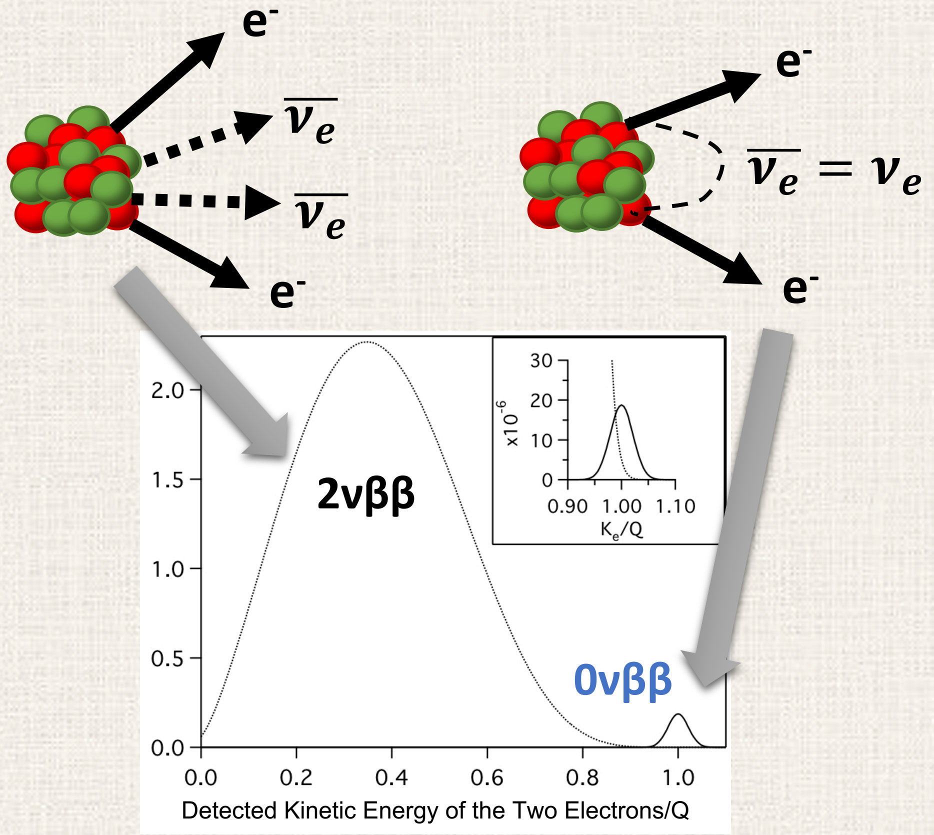
$$\left[T^{1/2}_{0\nu}\right]^{-1} = G_{0\nu}\left|\mathcal{M}_{0\nu}\right|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Phase Space Factor

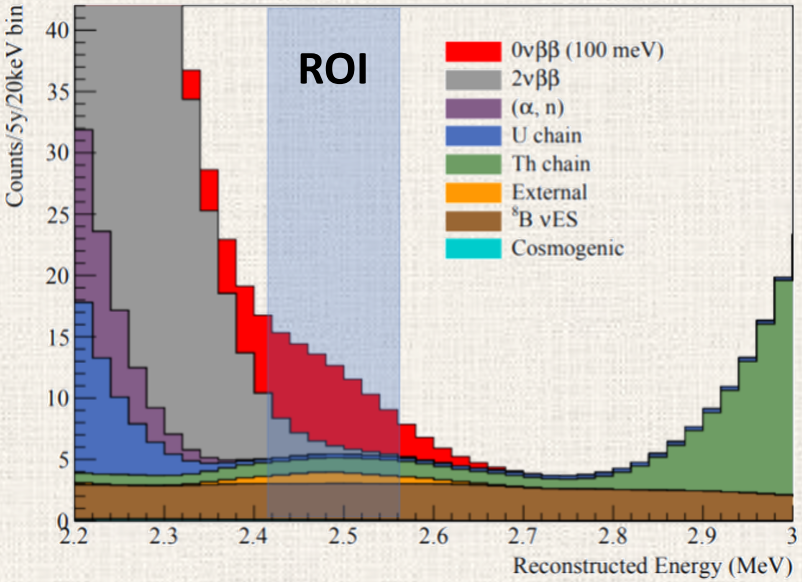
Nuclear Matrix Element (NME)

Effective Electron Neutrino Majorana Mass

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}\left|U^2_{ei}\right| m_i\right|$$



SNO+ Expected Energy Spectrum after 5 Years, Fiducial Volume of 3.3 m radius



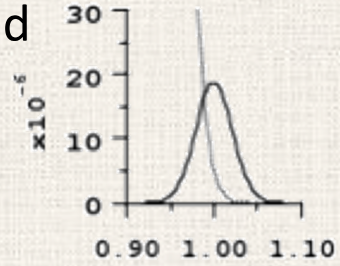
SNO+ Expected Half-Life Sensitivity after 5 years: 2.1×10^{26} years

$m_{\beta\beta}$ range 37-89 meV (model dependent)

$2\nu\beta\beta$-Decay of ^{130}Te

Measuring the 2νββ Spectrum Tail

- Allows to understand the background contribution of 2νββ to the 0νββ region-of-interest (ROI).

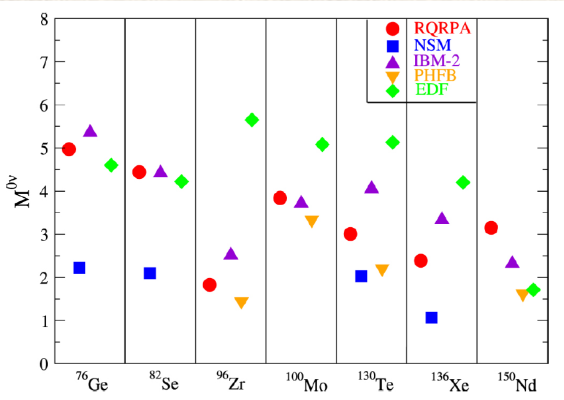


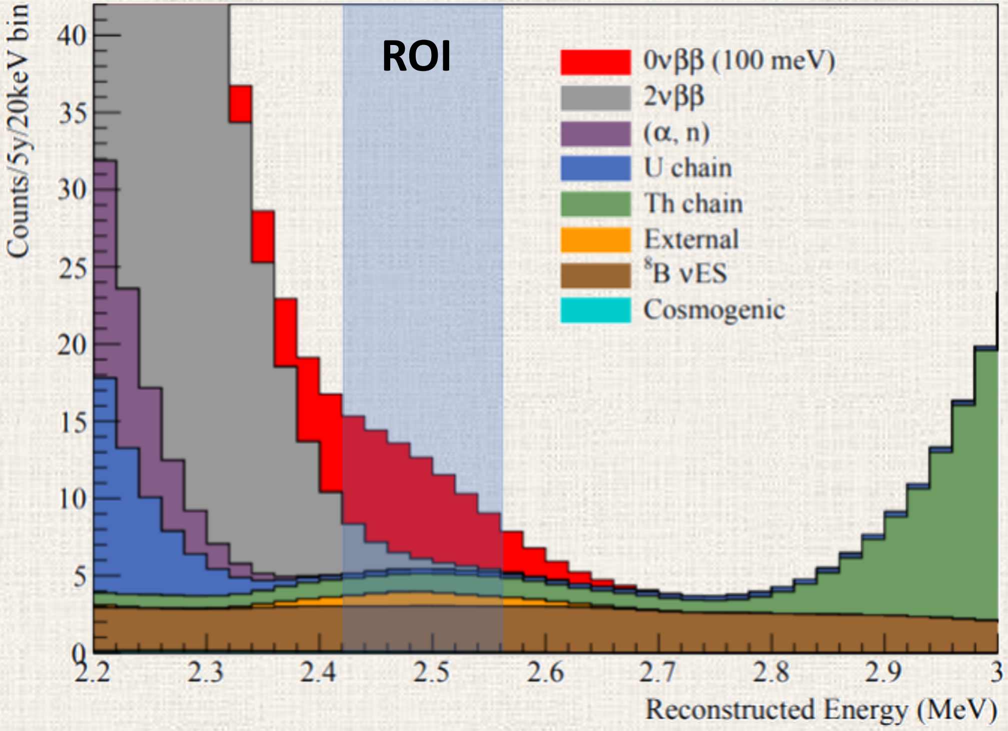
Measuring with precision the 2νββ Half-life

- Experimentally verify the nuclear models used for the NMEs calculation.

$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Nuclear Matrix Element (NME)





PhD Work Plan

Extract the ^{130}Te 2νββ-decay half-life by fitting the SNO+ data to the expected spectra and propagation of systematic uncertainties

Characterize the Detector Energy Response and Uncertainties - Optical and Energy Calibration

Create a Detailed Model of the Backgrounds and develop/optimize rejection techniques

1st Year	2nd Year	3rd Year	4th Year

Optical Calibration during the Water Phase (1st–2nd Year)
- Water attenuation + First in-situ measurement of Acrylic attenuation and PMT angular response up to 60 degrees
- Validation of the results using a gamma source

Currently used for the Water Data Set II Analysis and valuable inputs for the next phases

Background simulation speed-up (1st Year)
- Factor 1.5 improvement for external backgrounds

Monitoring the backgrounds during the scintillator fill (2nd–3rd Year)

Developing a Binned Likelihood Analysis for signal extraction (2nd–3rd Year)

Long term stay at SNOLAB (2nd Year)

^{7}Be Solar Neutrinos (3rd Year)

$2\nu\beta\beta$ Analysis – determine best ROI for fit, study shape variations (3rd Year)

4th Year:

Extracting the $2\nu\beta\beta$ half-life

Or

^{7}Be Solar Neutrinos Analysis

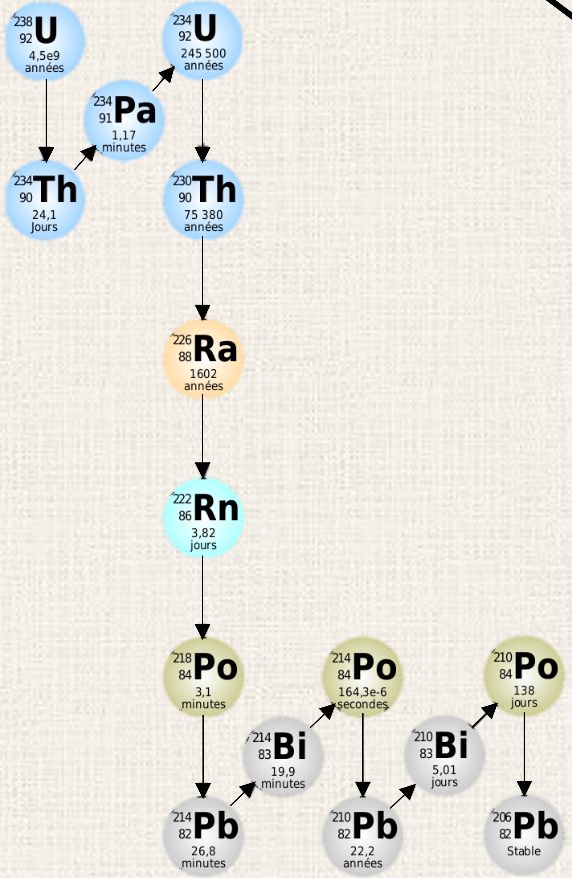
Dependent on SNO+ schedule

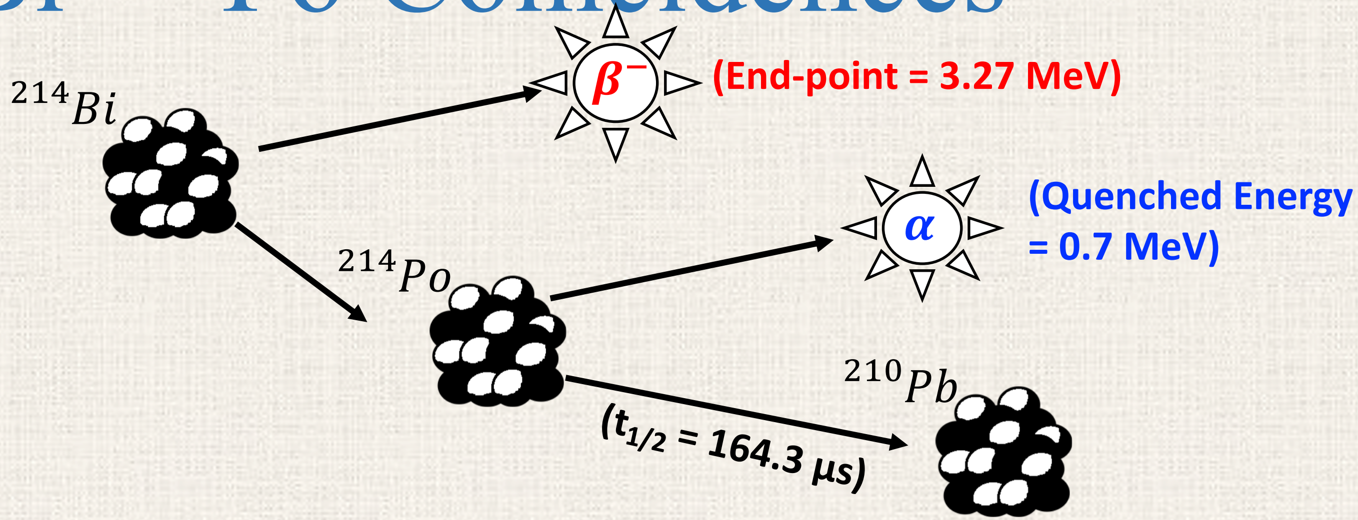
Monitoring the Scintillator Backgrounds during the Fill

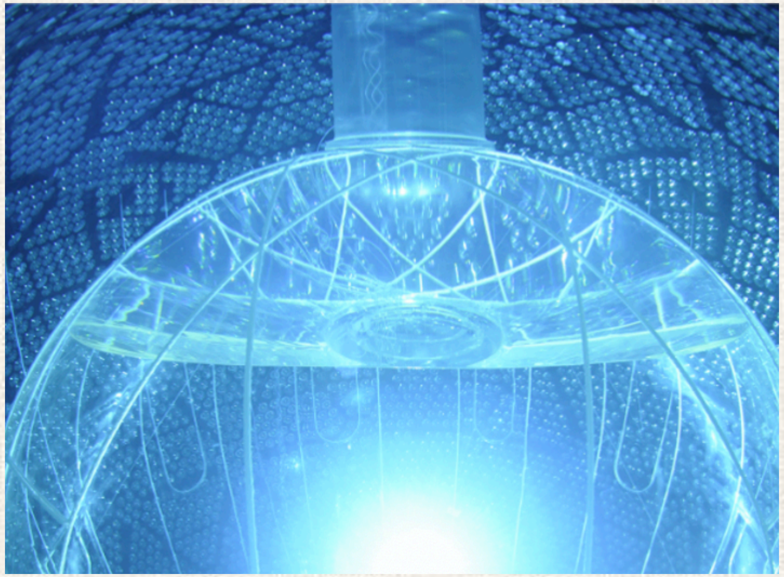
Tagging ^{214}Bi-^{214}Po coincidences, identify background contributions in the $0\nu\beta\beta$ region-of-interest

^{214}Bi-^{214}Po Coincidences

From the Uranium-238 decay chain

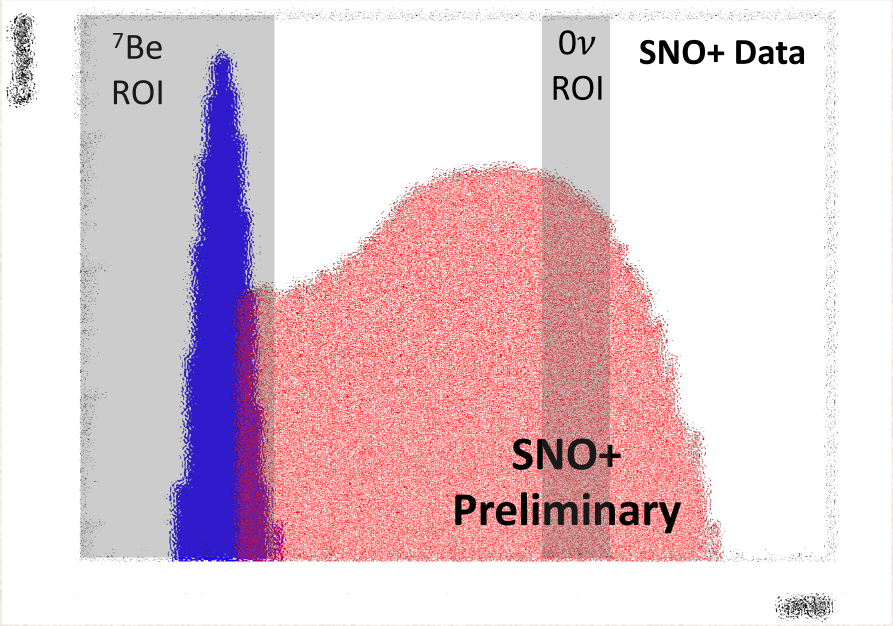






Target inside the scintillator for LS Phase: 1.0e-15 gU238/gLAB

SNO+ Acrylic = 1.0e-12 gU238/gLAB

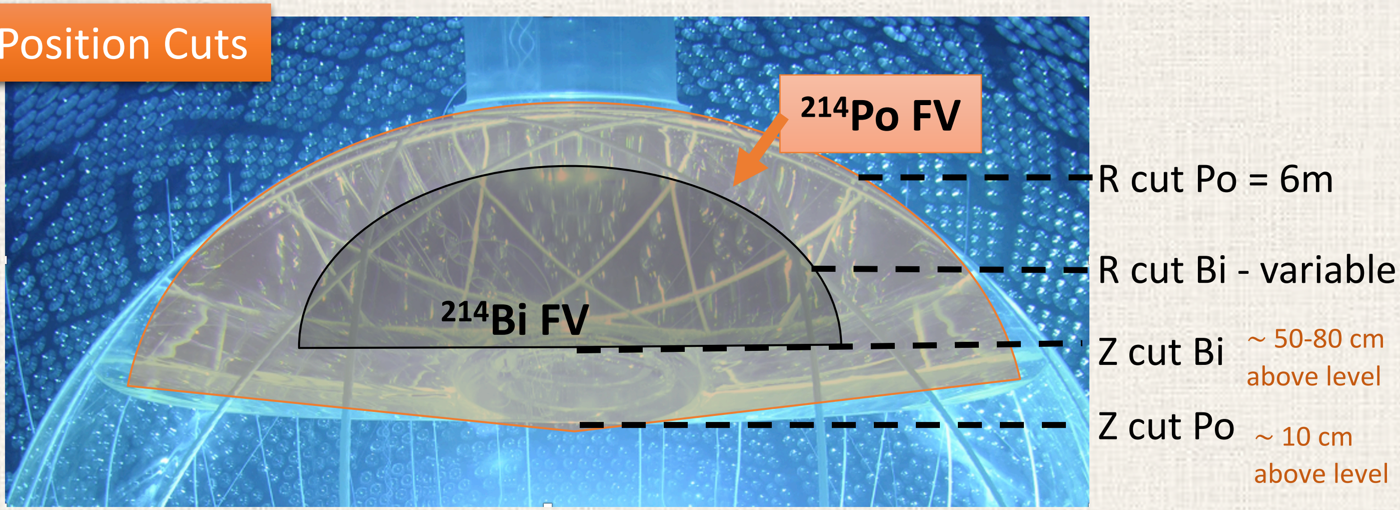


Background for the $0\nu/2\nu$ and ^{7}Be solar ν!

^{214}Bi-^{214}Po Coincidences

Use MC to optimize cuts and determine the tagging efficiency.

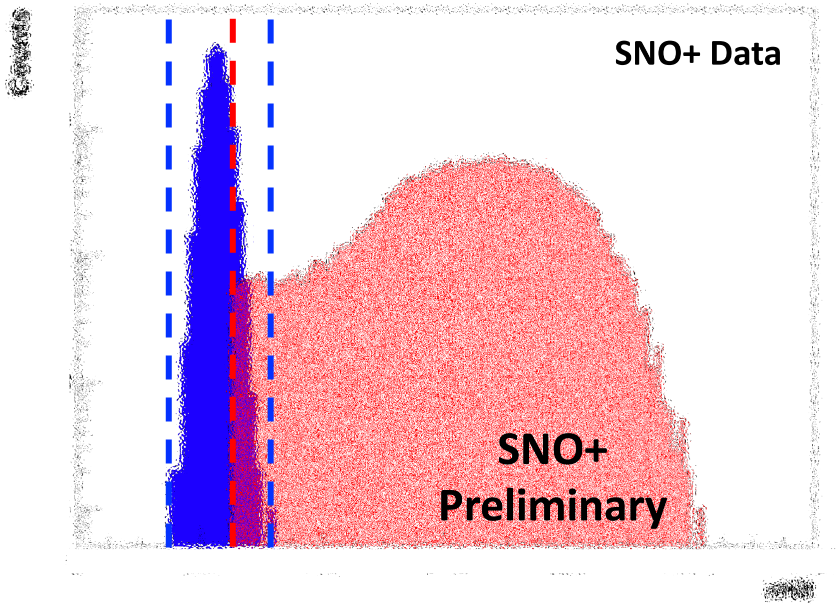
Position Cuts



Energy Cuts

Currently using number of hit PMTs -- nhit (proportional to energy). **Light Yield ~ 320 nhits/MeV**

- Bi: nhit > 250
- Po: 150 < nhit < 350



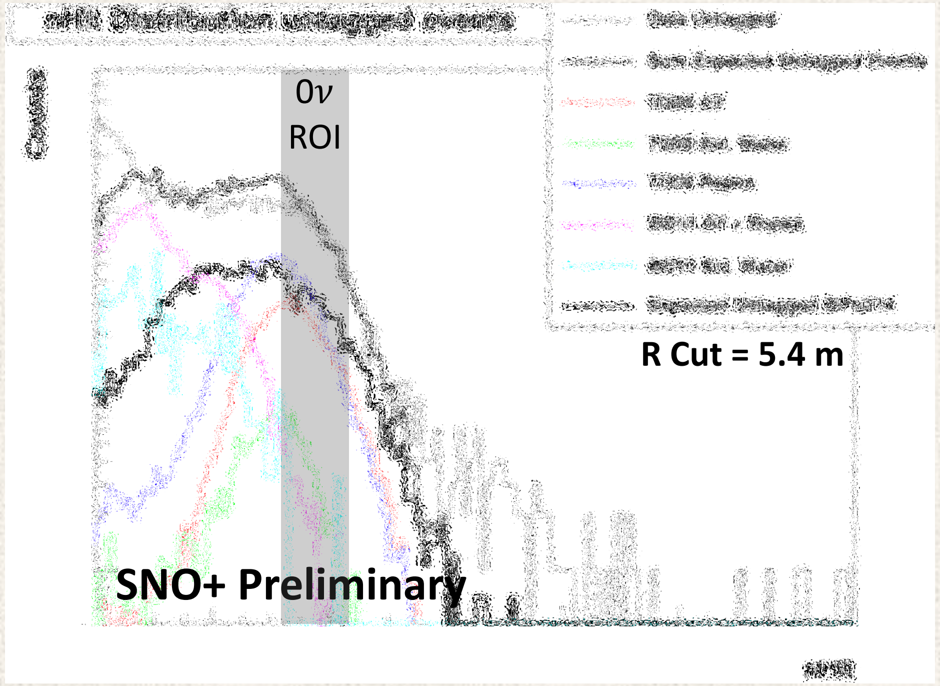
Tagging Method

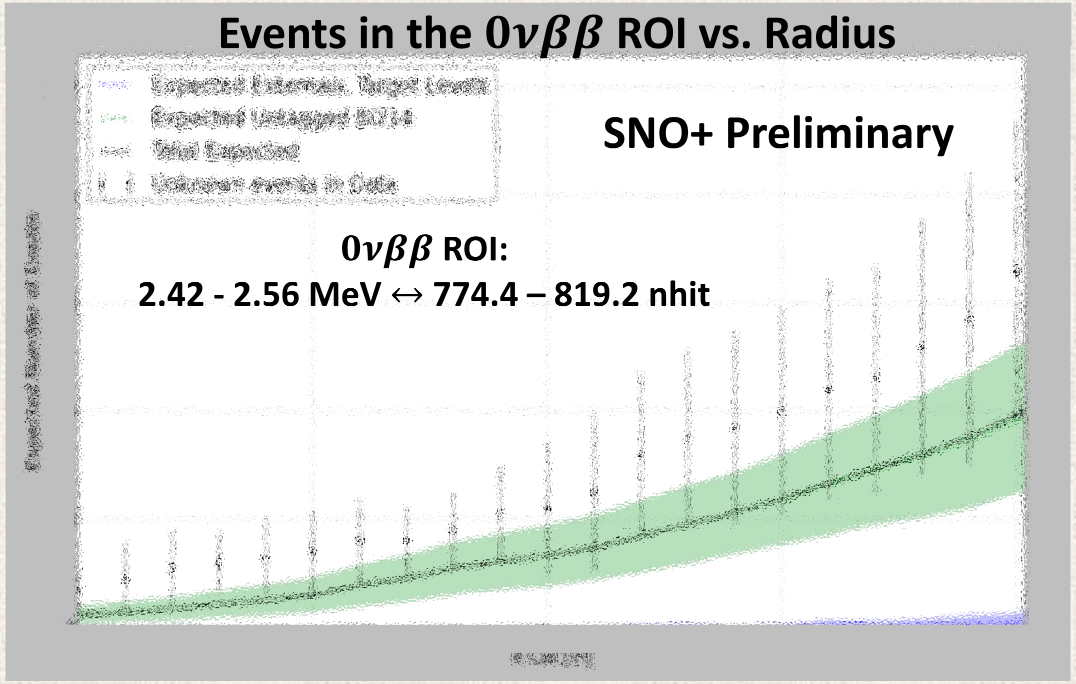
1) Find Bi candidate
2) Look for a Po candidate
   - Need to happen between 4 μs and 2 ms after the Bi candidate
   - Need to be up to 1 m away from the Bi candidate

98% efficiency across the scintillator volume!

^{214}Bi-^{214}Po Coincidences

Identify the Bi-Po events in data, reject them, and study the events left.





- Questions that I'm trying to answer with this analysis:

  Is the tagging efficiency in MC different than for data?

  Do we have other background contributions?

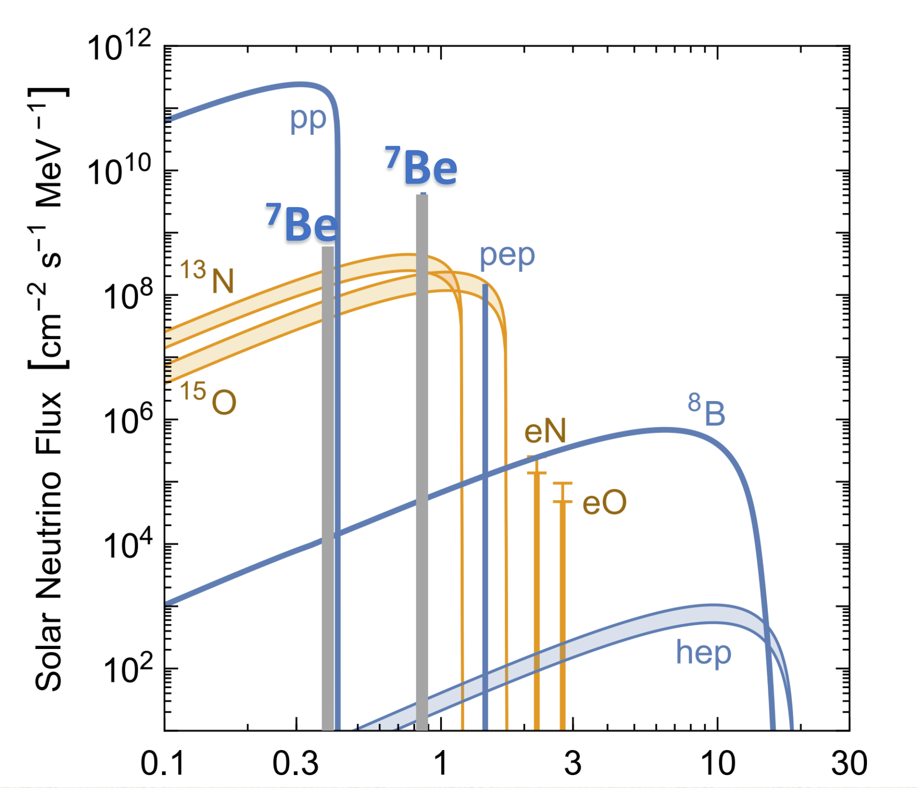
- On-going work for each new scintillator level, using stable detector periods.
- Also using the ^{214}Bi-^{214}Po coincidences to study the detector light yield.

^{7}Be Solar Neutrinos in the Partial Fill

^{7}Be Solar Neutrinos

- Relevant measurement:
  - Flux and flavour content are used to test the Standard Solar Model
  - Looking for time dependences (seasonal or day-night) of the event rate

  test different neutrino oscillation scenarios

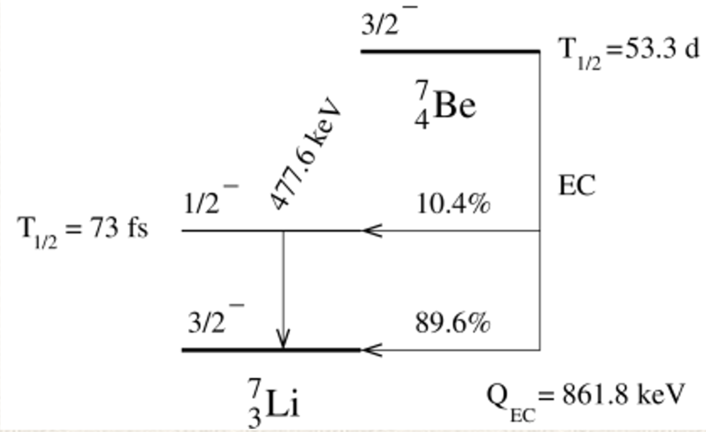


Standard Solar Model Expected Flux: $(4.93 \pm 0.29) \times 10^{9}$ cm^{-2} s^{-1} (GS98)

Borexino Measured Flux: $(2.79 \pm 0.13) \times 10^{9}$ cm^{-2} s^{-1} (assuming ν_e only)
$(4.43 \pm 0.22) \times 10^{9}$ cm^{-2} s^{-1} (considering 3-flavour oscillation)

- Cross-check with the SNO+ solar neutrino multi-component likelihood analysis.

^{7}Be Solar Neutrinos



B.R. 10.3%: ^{7}Be + e^{-} → ^{7}Li* + ν_e (E_ν = 0.386 MeV)

B.R. 89.7%: ^{7}Be + e^{-} → ^{7}Li + ν_e (E_ν = 0.863 MeV)

Expected Rate in SNO+

$$R = \Phi\, n \Big\{ 0.897 \times \Big(P_{ee}\sigma_{\nu_e}(E_\nu = 863keV) + (1 - P_{ee})\sigma_{\nu_\mu,\nu_\tau}(E_\nu = 863keV) \Big) + 0.103 \times \Big(P_{ee}\sigma_{\nu_e}(E_\nu = 386keV) + (1 - P_{ee})\sigma_{\nu_\mu,\nu_\tau}(E_\nu = 386keV) \Big) \Big\}$$

- Φ – ^{7}Be neutrino flux at Earth
- n – number of electron targets in the scintillator
- P_{ee} – electron neutrino survival probability
- σ_{ν_x} – total **neutrino-electron scattering** cross-sections

Calculated for each ^{7}Be solar neutrino energy

P_{ee} calculated considering:

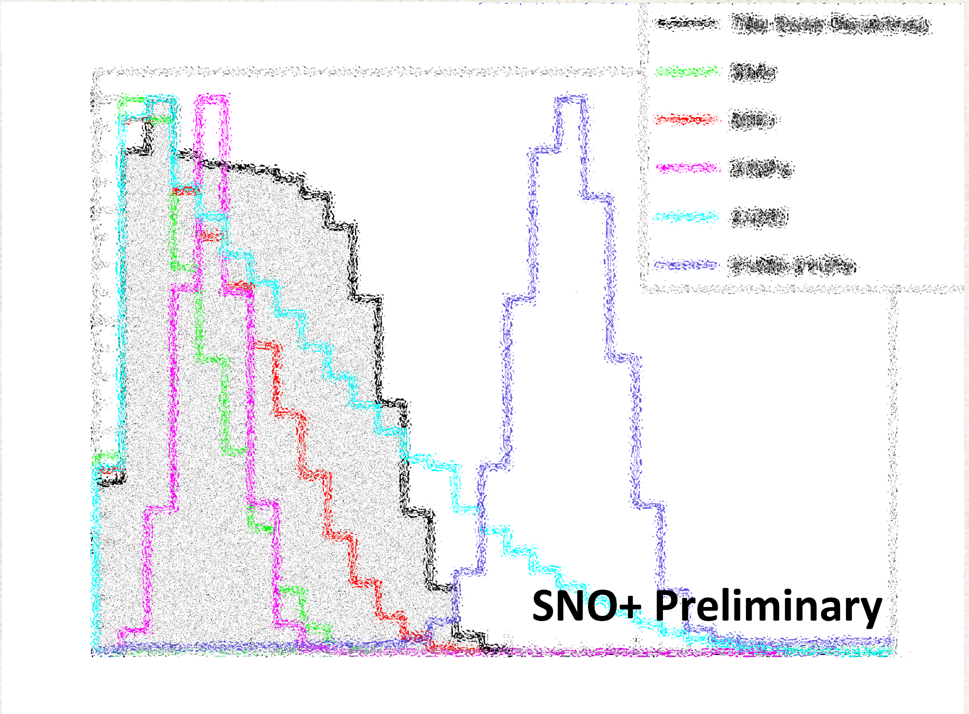
- the ^{7}Be ν production region in the Sun;
- the radial profile of e^{-} densities in the Sun.
- the best fit oscillation parameters from *M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018) and 2019 update*

Total of 17839 ν ES events/yr/100t

^{7}Be Solar Neutrinos

Currently, determining the background contributions and respective levels in the ^{7}Be ROI.

- Use alpha-beta classifiers, optimize cuts to reject externals, try directionality.



The final step will be to perform a Binned Maximum Likelihood fit of the MC p.d.f.s to the data.

- Evaluate uncertainties.
- Get a measurement or limit for the flux!

For *i* expected backgrounds and signal

$$log\mathcal{L} = -\sum_{i=1}^{N_{norms}} N_i + \sum_{j=1}^{N_{bins}} N_{obs}^{j}\, log\left(\sum_{i=1}^{N_{norms}} N_i\, P_i^j\right)$$

Normalisations for each type *i*

counts observed in bin *j* (data)

Value of the p.d.f for event type *i* in bin *j*

Summary

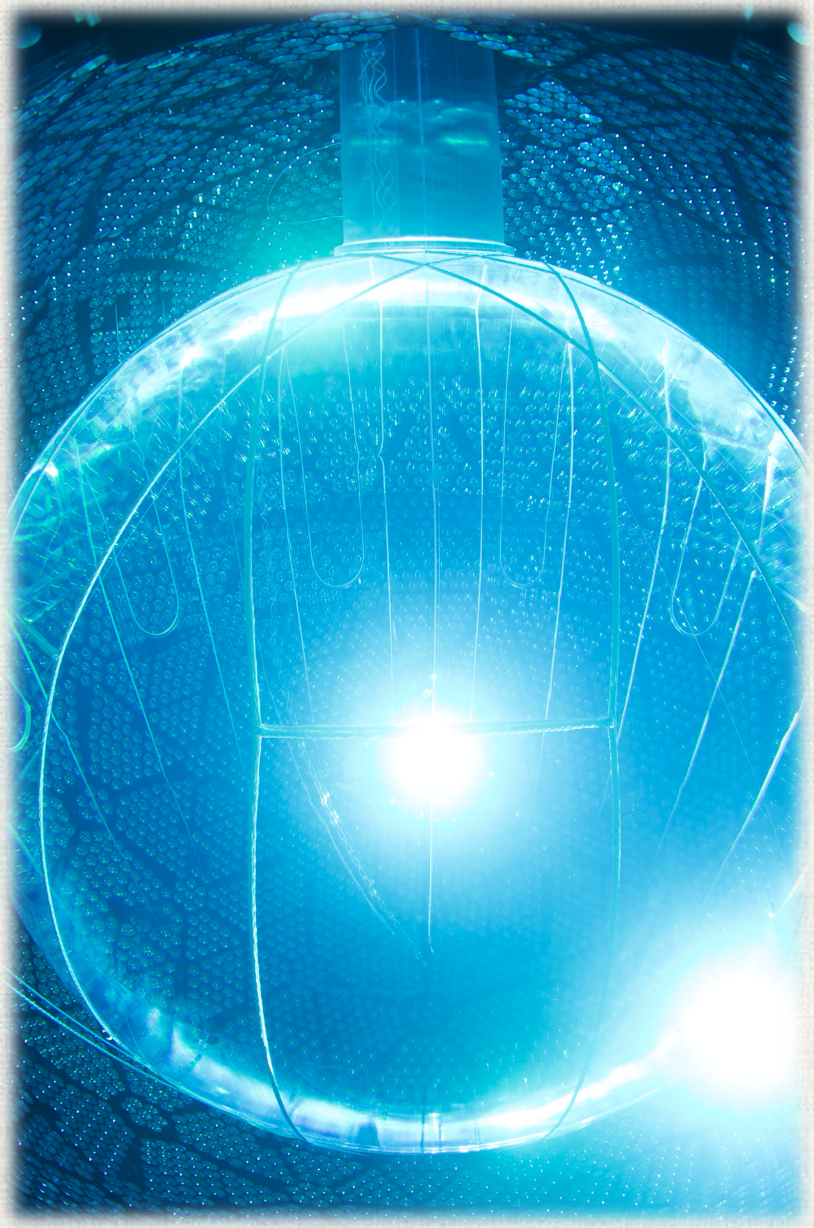
SNO+ moving towards Scintillator Phase!

Detector ½ filled!

- Monitoring the backgrounds during the scintillator fill.
  - On-going work, adapting to the different fill levels.

- Developing a Signal Extraction Analysis, based on a binned maximum likelihood fit → Tool for signal extraction.

- Starting analysis of ^{7}Be Solar Neutrinos in the scintillator phase.



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