SNO+ in sntools

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Introduction

In this talk:

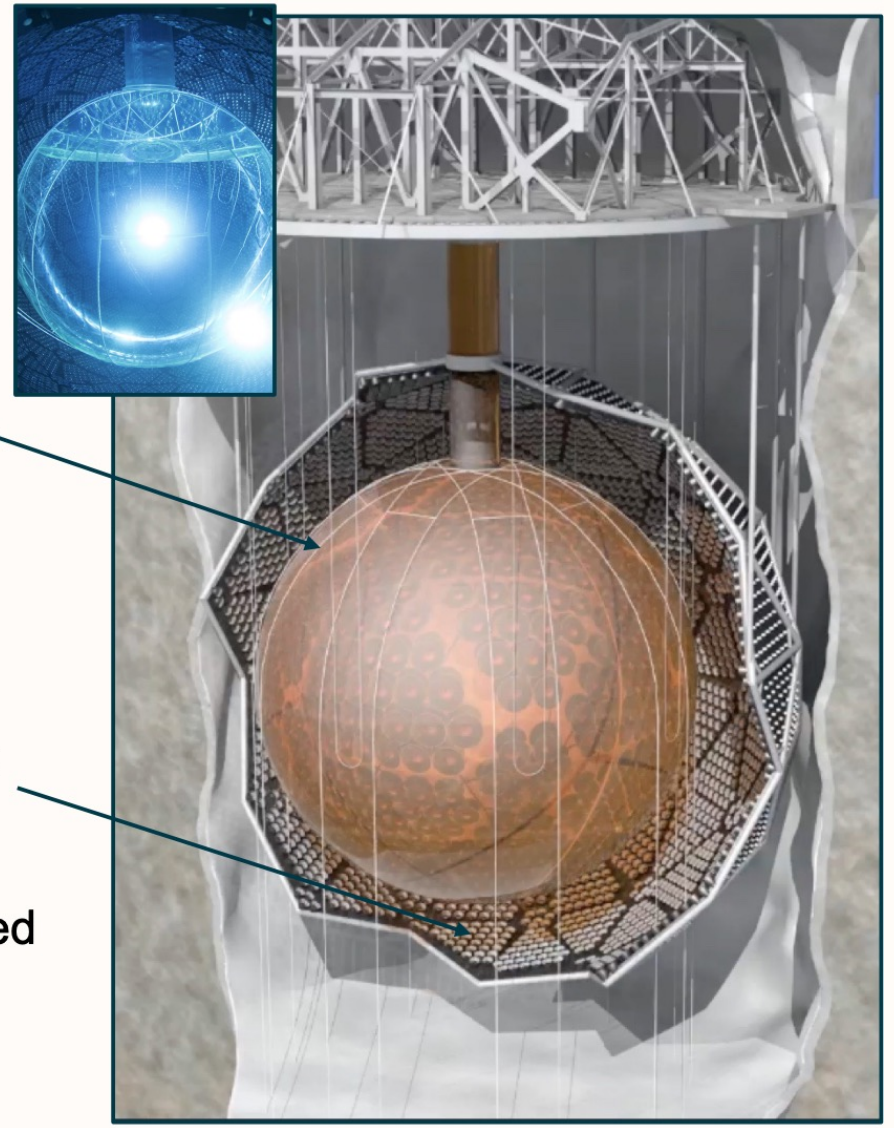
- The SNO+ Experiment
- How do Supernova Neutrinos interact with SNO+
- Event generator options
- Integrating SNO+ into sntools
- Validation study
- Current progress and future ideas

SNO+ Experiment

- Upgrade from Sudbury Neutrino Experiment (SNO) which won the Nobel Prize in Physics in 2015.
  https://www.nobelprize.org/uploads/2018/06/mcdonald-lecture-slides.pdf
- Housed in SNOLAB, Sudbury, Canada.
- Multi-purpose neutrino experiment.
  - Primary research goal is neutrinoless double-beta decay ($0\nu\beta\beta$).
  - Broad physics program includes, solar and reactor neutrino oscillations, geoneutrinos and ***supernova neutrino detection***, nucleon decay, and dark matter detection
- Albanese, V., et al. "The SNO+ experiment." *Journal of Instrumentation* 16.08 (2021): P08059. https://arxiv.org/abs/2104.11687

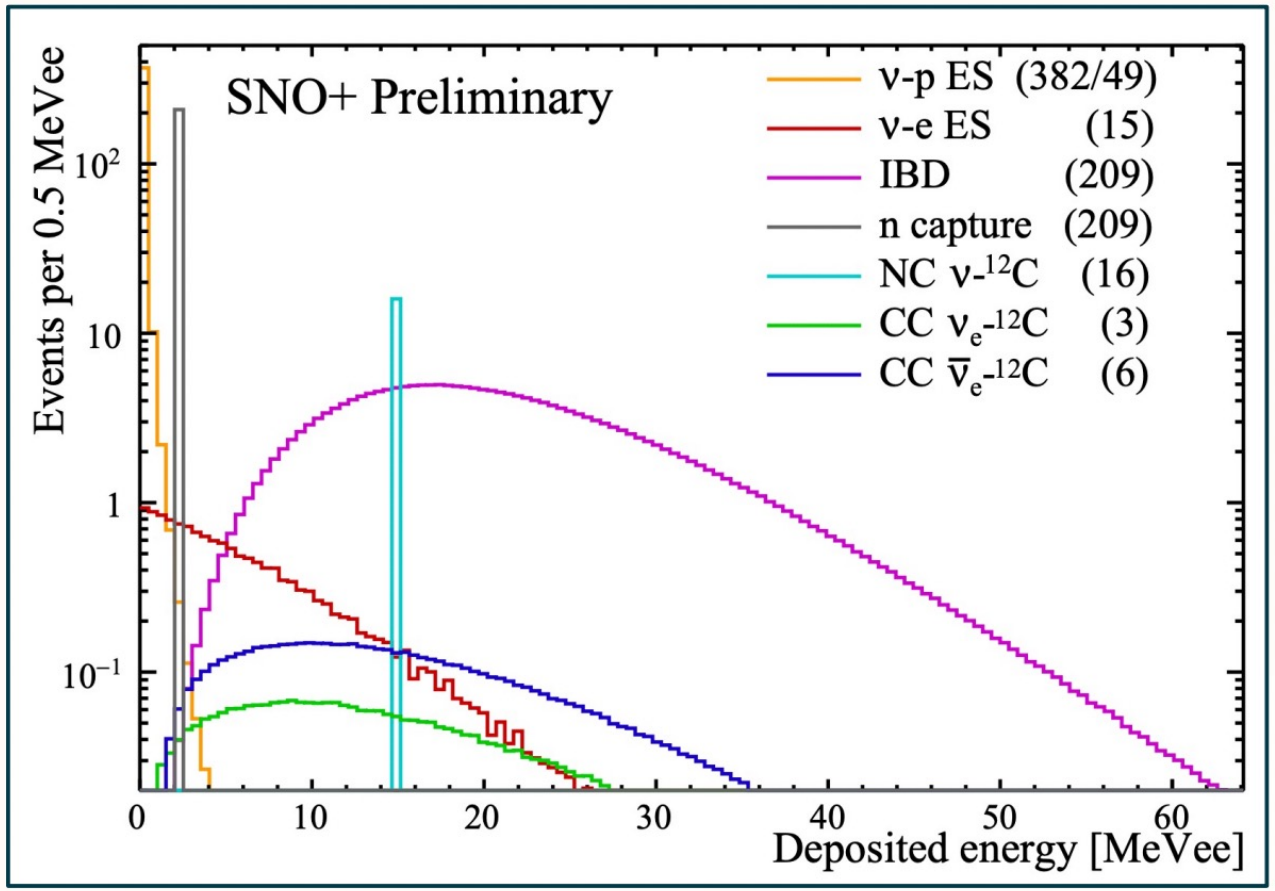
SNO+ Experiment

- 2 km underground, ~6000 MWE
- 12 m diameter Acrylic Vessel (AV):
  - Filled with 780 tonnes of liquid scintillator:
    - LAB + [target of] 2 g/L PPO
    - To be loaded with ^{130}Te for double beta decay studies
- Surrounded by 7 kT of external ultra-pure water
- Viewed by ~9300 (8”) PMTs mounted on a 17 m diameter PMT support structure (PSUP)
- AV is now full filled with liquid scintillator. Currently loading PPO, planned to start adding ^{130}Te at the end of 2022

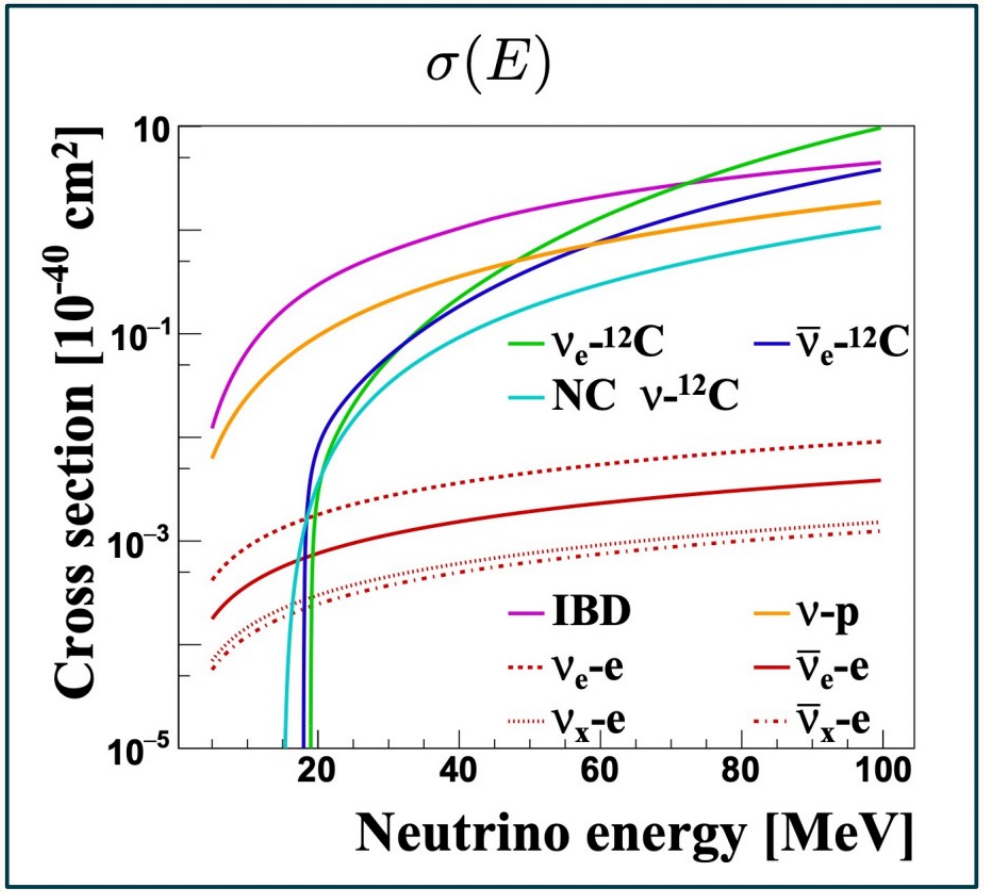


Interaction Channels in LAB

Supernova neutrino interaction channels available to SNO+ *inside* the AV



Cross-sections of interaction channels available to SNO+ *inside* the AV



Event Generators

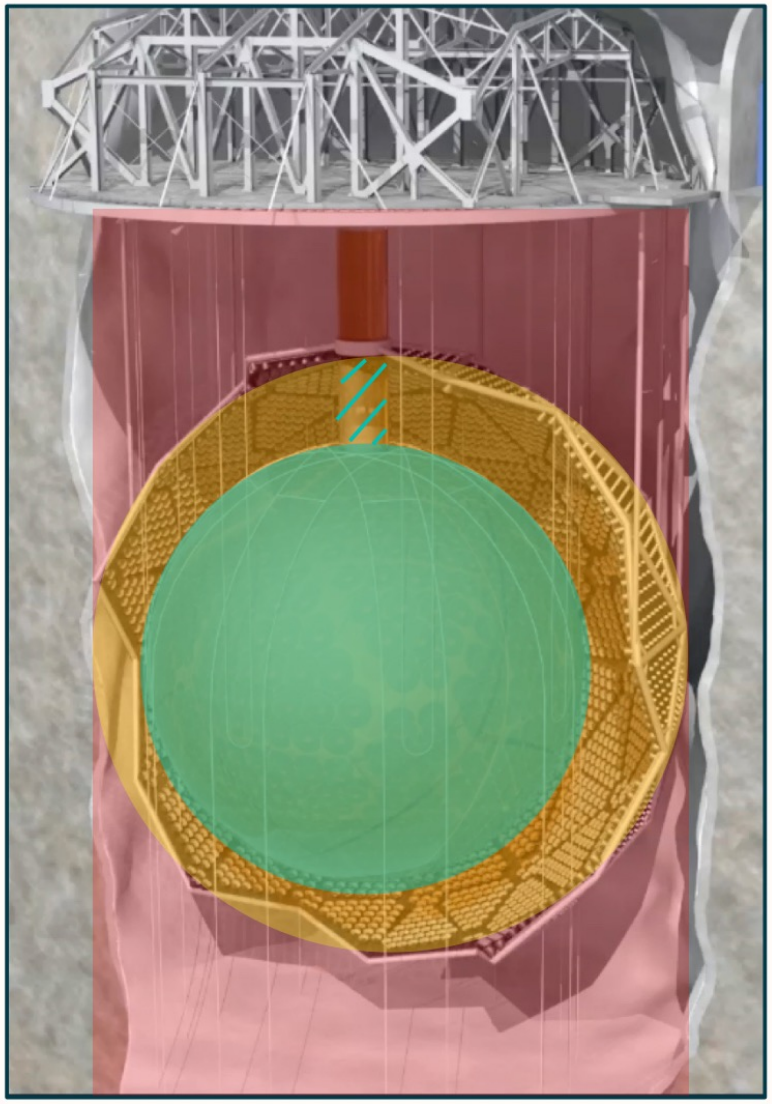
- We have previously used **SNUGen** for a lot of the SN studies in SNO+
  - Relatively difficult to learn/use
  - Messy – written by different people over long period of time
  - Limited in interaction channels and models available
- Therefore used an opportunity to re-evaluate the event generator we use, potential candidates:
  - **SNOwGLoBES** – commonly used, not *really* an event generator
  - **snewpy** – large array of models available, used by SNEWS, front-end for SNOwGLoBES
  - **EstrellaNueva** – analytical techniques, not a bad word to say about this one ;)
  - **sntools** – previously used for HK/SK/WATCHMAN, utilises snewpy for flavour transformations and SN models (versatile), easy-to-use, good potential candidate to replace SNUGen

Let's explore sntools…

SNO+ in sntools

- Added SNO+ detector geometry into sntools:
  - Inner AV filled with liquid scintillator (see next slide) implemented, tested, and working! – Note neck is not implemented!
  - External water (inside PSUP) has been implemented, tested, and working!
  - External water (outside PSUP) not implemented… still thinking if this is needed

- Inner AV called using `--detector SNOplusAV`
- External water is called using `--detector SNOplusEW`
- Note: the addition of SNO+ led to two new shapes available in sntools called “sphere” and “hollow sphere”



SNO+ in sntools

- Previous liquid scintillator in sntools is approximated to CH_2
- This does effectively represent Liquid Alkylbenzene (LAB)
  - Added LAB $C_6H_5C_nH_{2n+1}$
    - Alkyl part $9 < n < 14$ (95% $9 < n < 12$); averaged out to approximate* $C_{16.65}H_{27.3}$ with mW = 227.5 g/mol
- Interaction modes: IBD, ν – e elastic scattering, ν_e – CC – ^{12}C, ν_e – NC – ^{12}C, ν – p elastic scattering (see next slide)

```
12 # liquid scintillator: approximated here as CH_2
13 ls = {
14     "molecular_weight": 14.0266,  # g/mol
15     "density": 0.86,  # g/cm^3
16     "channel_weights": {"ibd": 2, "es": 8, "c12e": 1, "c12eb": 1, "c12nc": 1},
17 }
18
19 # liquid scintillator: LAB, average structure -> C_16.65H_27.3 (C6H5CnH2n+1 where n is 95% 9-12, 5% 13-14)
20 lab = {
21     "molecular_weight": 227.50,  # g/mol
22     "density": 0.856,  # g/cm^3
23     "channel_weights": {"ibd": 27.3, "es": 127.2, "c12e": 16.65, "c12eb": 16.65, "c12nc": 16.65, "ep": 27.3},
24 }
25
```

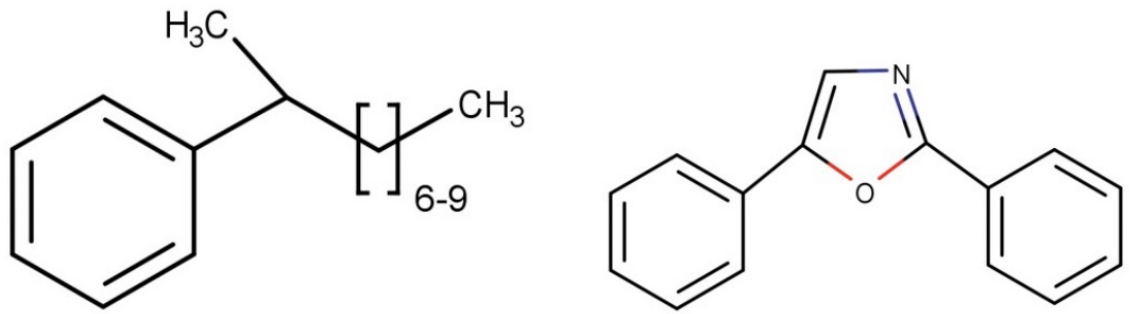
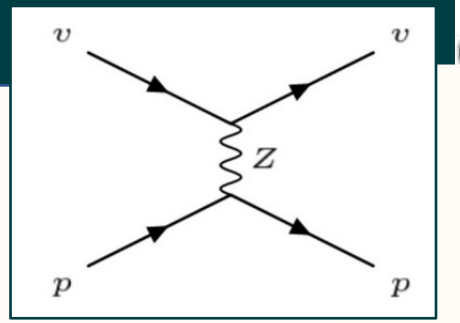


Figure 2: Structural formulae of the two primary components of the SNO+ scintillator cocktail. Left: LAB is a phenyl group attached to a carbon chain varying between 9–14 (>95% 9–12) carbons in length. Right: PPO is the fluorophore of the liquid scintillator cocktail.

*NB: GCMS to be run soon to get chain length proportions – can update once known

SNO+ in sntools



- ν – p elastic scattering was not previously implemented in sntools
- NC interaction; available to all flavours of (anti)neutrinos
- Few MeV protons are invisible in water Cherenkov detectors, but is possible to see them in liquid scintillator! Meaning ν – p elastic scattering is a channel available to SNO+
- The channel is as the proton recoil spectrum provides spectral information about the incoming neutrino
  - Can in theory measure the neutrino energy through this NC channel
- Total cross-section is about factor 3 smaller than IBD and is potentially the second largest signal in SNO+
- This channel is available to other SN event generators e.g. SNUGen and EstrellaNueva
- Implemented (tested and working) in sntools in `interaction_channels/ep.py` ← Note: name to change
- Implementation largely based on J. Beacom, 2002: https://arxiv.org/pdf/hep-ph/0205220.pdf

Validation

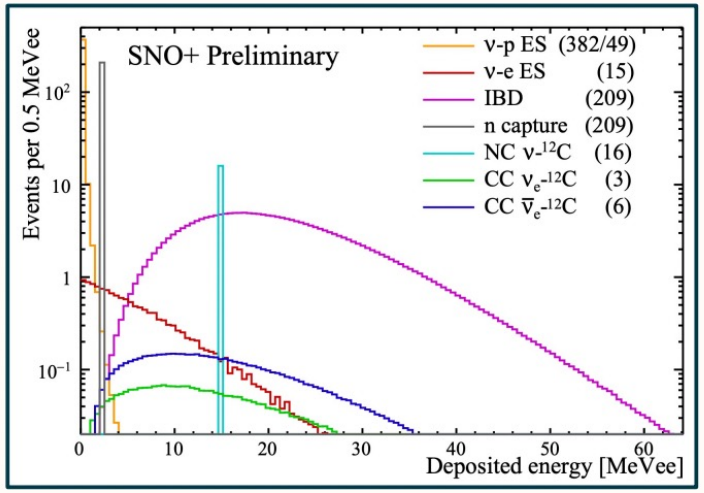
	sntools	SNUGen	EstrellaNueva	SNO+ Preliminary
IBD	207.9 ± 1.4	212	203	209
es	14.0 ± 0.4	14	14	15
ep	377.5 ± 1.9	395	382	382
c12e	3.4 ± 0.2	-	5	3
c12eb	5.3 ± 0.2	-	6	6
c12nc	15.8 ± 0.4	-	16	16
Total	623.9 ± 2.5	621*	626	631

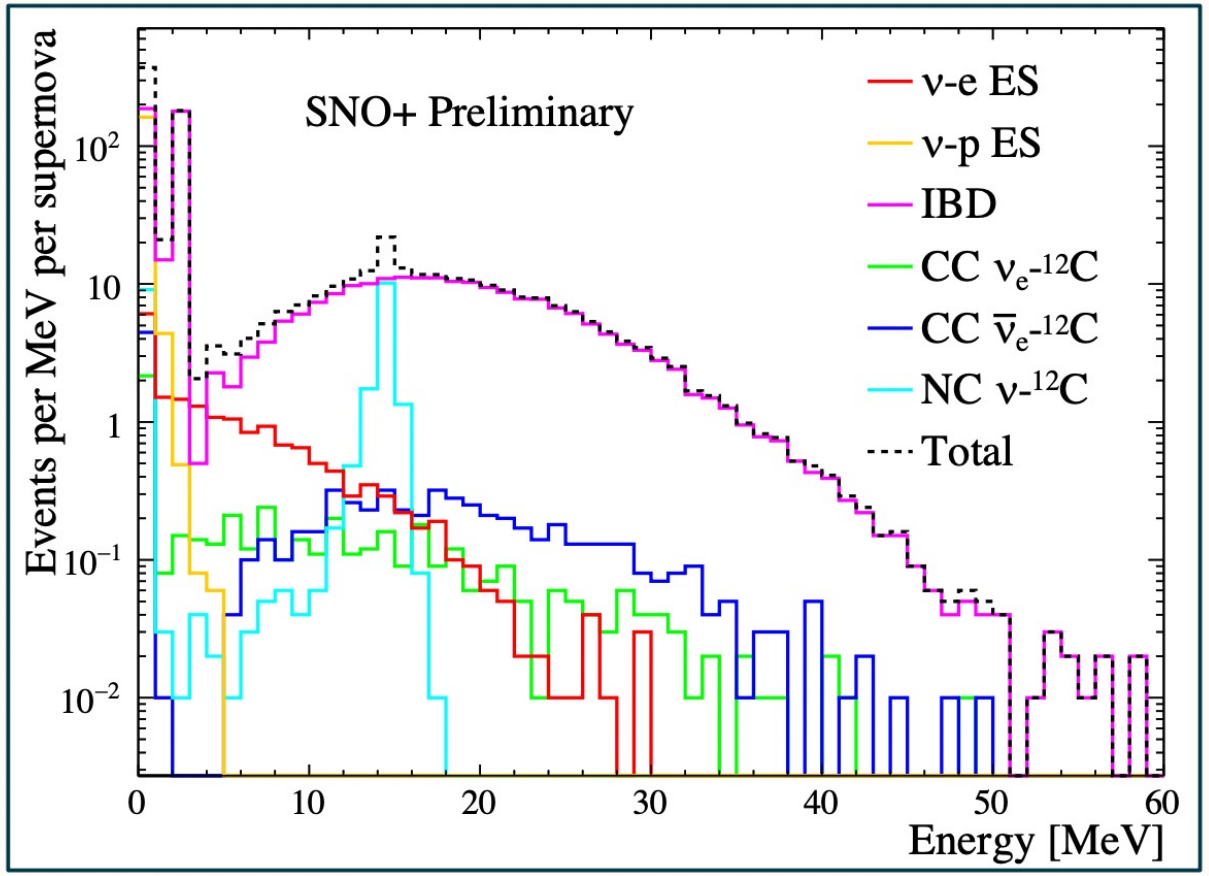
* SNUGen does not include interactions on C12.

- Comparison of event rates expected per supernova for each topology in the SNO+ inner AV
- sntools appears to agree relatively well with SNUGen, EstrellaNueva, and the SNO+ preliminary plots
- Systematically lower event rates is due to the lower number of target nuclei when estimating the chemical composition of LAB
- Errors quoted here are statistical uncertainties (over 100 supernovae)
- Event rates are calculated using LS220_s27.0co SN model at 10 kpc

Event Generation

- SNO+ recently integrated with sntools[1] to simulate supernova neutrinos in the detector
- Generated events for 100 supernovae – renormalise to predict sensitivity per example[2] supernova
- Run through detector simulation to include energy smearing and reconstruction
- Can measure NC ν-^{12}C through 15.1 MeV excitation





[1] Migenda et al., (2021). sntools: An event generator for supernova burst neutrinos. Journal of Open Source Software, 6(60), 2877, https://doi.org/10.21105/joss.02877

[2] A. Mirizzi et al. Rivista del Nuovo Cimento Vol. 39 N. 1-2 (2016)
[with 27$M_\odot$ progenitor CCSN with LS220 equation-of-state, at 10 kpc]

Current Status

- PR #42 – SNO+ integration in sntools is almost complete
  - Comments mostly corrected, testing complete, documentation to be written
  - Apologies for delays – situation less than idea, but aim to have this done by the end of the month
- Sntools is now becoming the default SN MC event generator for SNO+ (alongside EstrellaNueva)
  - Being used in directionality studies – Josie Paton
  - Extracting time of core bounce – Remington Hill
  - Investigating other potential uses, e.g. Flavor transformation, NMO, re-evaluation of SN sensitivities – Sammy Valder

Future Plans:

- Short term – finish PR, fix any inevitable short term bugs
- Long term – become default SN event generator for SNO+ (alongside EN), possibilities are almost endless!

Summary

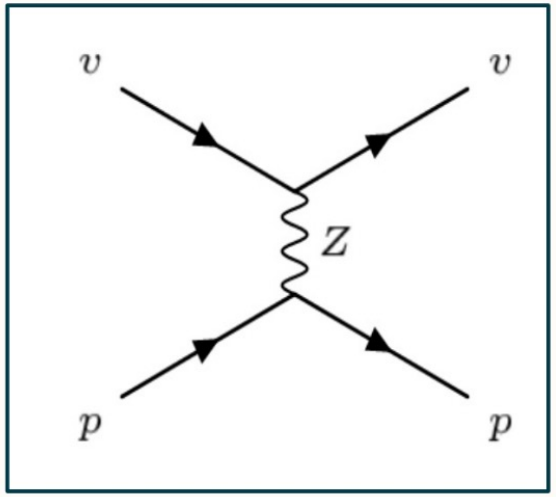
- SNO+ is now filled with liquid scintillator which gives greater sensitivity to supernovae and access to new interaction channels
- The expected supernova signal at SNO+ is well understood
- SNO+ has been integrated within sntools, current validation studies and testing appear to show it's working as expected
    - PR to be completed asap (hopefully end of this month) – essentially just documentation to be written
- Sntools is already starting to be used as an event generator for preliminary SN analyses in SNO+
    - With sntools' flexibility, the possibilities here are far and wide

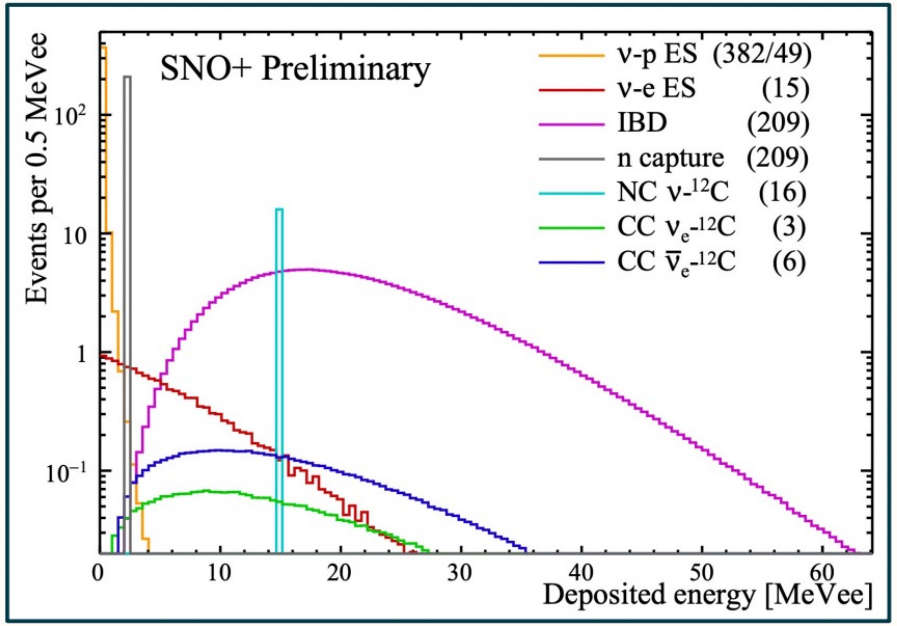
Backups

Proton Scattering

- Few MeV protons are invisible in water Cherenkov detectors, but is possible to see them in liquid scintillator → available to SNO+
- Neutral current (NC) interaction → sensitive to all neutrino flavours
- Proton recoil spectrum provides spectral information about incoming neutrino → measure neutrino energy
- Difficult to detect
- Signal will be quenched in the detector
  - 382 events predicted†, 49 events above 200 keV threshold after proton quenching
  - Second largest SN signal in SNO+

† $27M_{\odot}$ progenitor CCSN with LS220 equation-of-state, 10 kpc away





Proton Scattering

ν – p elastic scattering implementation largely based on J. F. Beacom *et al.*, *Phys Rev D* 66(3), 2002

Differential cross-section: $$\frac{d\sigma}{dT_p} = \frac{G_F^2 M_p}{2\pi E_\nu^2}\left[(c_V + c_A)^2 E_\nu^2 + (c_V - c_A)^2 (E_\nu - T_p)^2 - (c_V^2 - c_A^2) M_p T_p\right]$$

c_A is +ve (-ve) for refers to (anti)neutrinos

Recoil energy/angle of proton: $$\cos\theta_p = \frac{E_\nu + M_p}{E_\nu}\sqrt{\frac{T_p}{T_p + 2M_p}} \simeq \sqrt{\frac{M_p T_p}{2E_\nu^2}}$$

Maximum recoil energy of proton: $$T_p^{max} = \frac{2E_\nu^2}{M_p + 2E_\nu} \simeq \frac{2E_\nu^2}{M_p}.$$

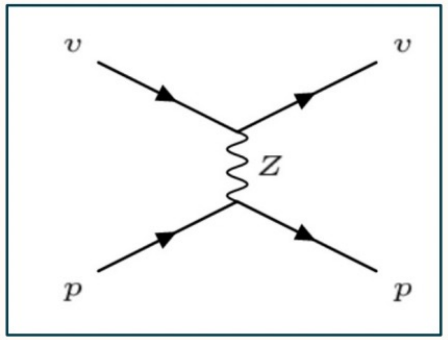
Minimum energy of incoming neutrino: $$(E_\nu)_{min} = \frac{T_p + \sqrt{T_p(T_p + 2M_p)}}{2} \simeq \sqrt{\frac{M_p T_p}{2}}.$$

Assuming $(E_\nu - T_p)^2 \simeq E_\nu^2$ is a "very good" approximation at SN neutrino energies

Coupling constants:

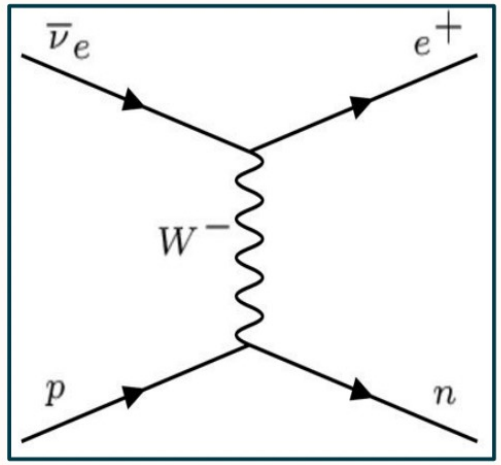
$$c_V = \frac{1 - 4\sin^2\theta_W}{2}$$

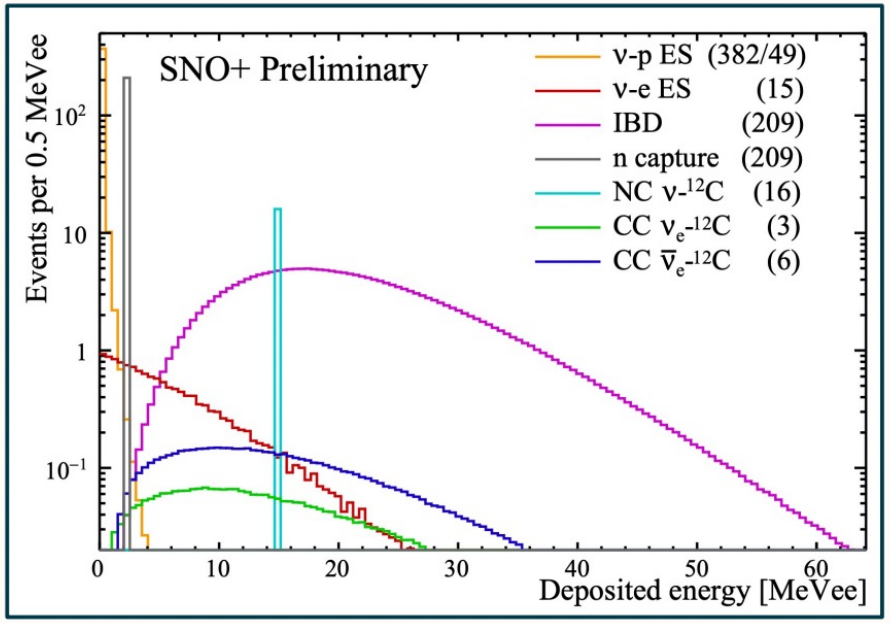
$$c_A = \frac{g_A(0)\cdot(1+\eta)}{2}$$



IBD

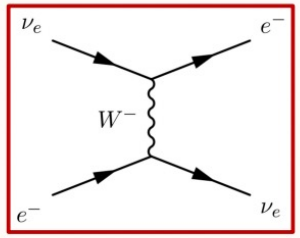
- Anti (electron)neutrino undergoes charged current (CC) interaction with proton to produce positron and neutron
- Outgoing positron detected as spectrum
- Neutron capture on proton produces 2.2 MeV delayed photon
  - Easy to tag
- Largest signal from supernovae in SNO+
  - 209 events expected from example† SN at 10 kpc

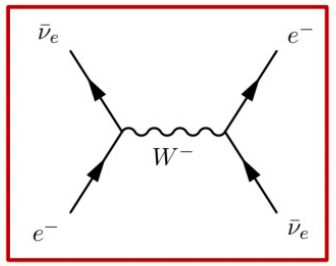


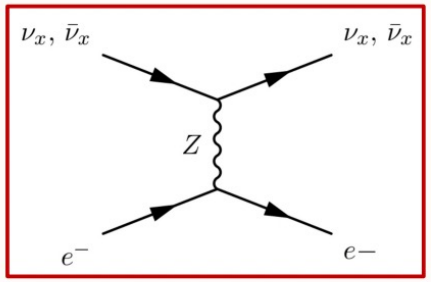


† $27M_\odot$ progenitor CCSN with LS220 equation-of-state

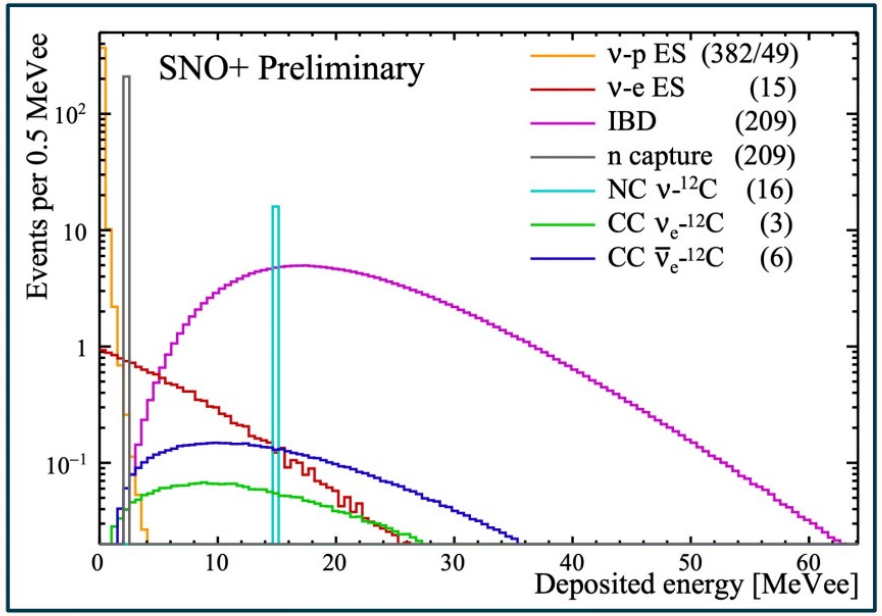
Other Interactions







- Flavour dependent cross-section
- ν_e and $\nu_e \rightarrow$ CC interactions
- $\nu_x \rightarrow$ NC interactions



$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N} + e^-$$

ν_e Charged Current on ^{12}C

$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B} + e^+$$

$\bar{\nu}_e$ Charged Current on ^{12}C

$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$$

ν_x Neutral Current on ^{12}C

- Distinctive 15.1 MeV excitation
- Cross-section measured by Karmen