Detection of Supernova Neutrinos in the SNO+ Detector

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Detector

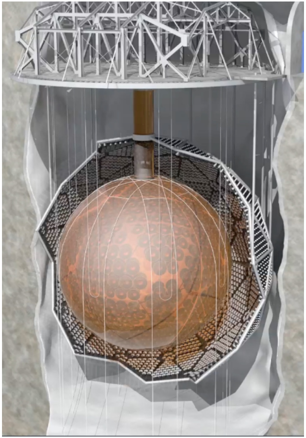

Figure: Artist rendering of the SNO+ detector

Sudbury **N**eutrino **O**bservatory **+**

- 2km underground in SNOLAB facility
- inner acrylic vessel with 12 m diameter, viewed by 9362 photomultiplier tubes (PMTs) mounted onto a PMT support structure (PSUP)
- external volume of 7000 tonnes of ultra-pure water (UPW) shielding the AV from the PSUP and cavity

Phases

Water Phase

905 tonnes of UPW
May 2017 — July 2019
Results include ^{8}B solar neutrino flux, neutron detection, calibration

Scintillator Phase

780 tonnes of linear alkylbenzene (LAB)
Doped with fluor 2,5-diphenyloxazole (PPO) at a concentration of 2.2 g/L
Began in April 2022, in progress

Te Loading Phase

Loading the LAB with ^{130}Te
Development in progress
Measuring lifetime of $2\nu\beta\beta$ decay and the search for $0\nu\beta\beta$

Physics Goals

1. The search for neutrinoless double beta decay, $0\nu\beta\beta$;
2. Geoneutrino emissions;
3. Oscillation of reactor anti-neutrinos;
4. Low energy solar neutrino flux and spectral shape;
5. **Sensitivity to supernova neutrinos**;

... and many more exotic physics topics.

[Albanese et al., 2021]

Core-Collapse Supernovae

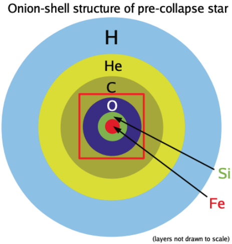

Figure: [Janka et al., 2012]

- The stellar core mass passes the Chandrasekhar limit, $\approx 1.4 M_{\odot}$ [Woosley et al., 2002]
- Exceeding this, the radiation and degeneracy pressure are no longer sufficient to balance the gravitational force
- $E \approx 10^{53}$erg is released; most of it in the form of neutrinos

Neutrino Emission

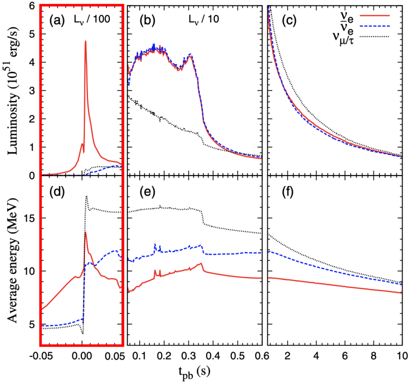

Figure: Neutrino luminosity and energy for an $18M_\odot$ progenitor star.

- A *neutrino-sphere* is created when ν diffusion time $>$ time of free fall collapse
- As the outward shock-wave crosses the neutrino-sphere there is a burst of ν_e

Bounce

When the core reaches nuclear density, and neutron degeneracy pressure suddenly stalls the collapse, resulting in an outward propagating shock-wave.

Neutrino Emission

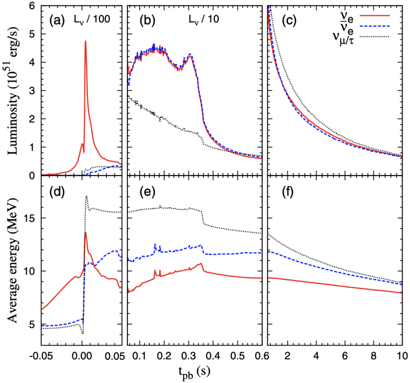

Figure: Neutrino luminosity and energy for an $18M_\odot$ progenitor star.

- Neutrinos of all flavours continue to be produced through accretion and cooling phases
- The emission occurs over $\mathcal{O}$(10s), and has the strongest overall signal in the ν_e luminosity
- Energy range $\approx$ 10-20 MeV
- $E_{\nu_{\mu/\tau}} > E_{\bar{\nu}_e} > E_{\nu_e}$

What Can be Learned

Supernova Physics

- Neutrino absorption via inverse beta decays contributes energy believed to 'revive' the shock-wave, which stalls at the accretion phase [Bethe and Wilson, 1985]
- Sites for nucleosynthesis and the rapid neutron capture responsible for heavy element production [Arcones and Thielemann, 2012]

Neutrino Physics

- More detailed knowledge on neutrino oscillations through dense matter and neutrino self interactions and their collective effects on the flux spectra [Duan et al., 2006]

Detection Channels

Past Detection

The only previous confirmed detection of supernova neutrinos came with SN1987A, which generated 24 total events observed in three different detectors.[1]

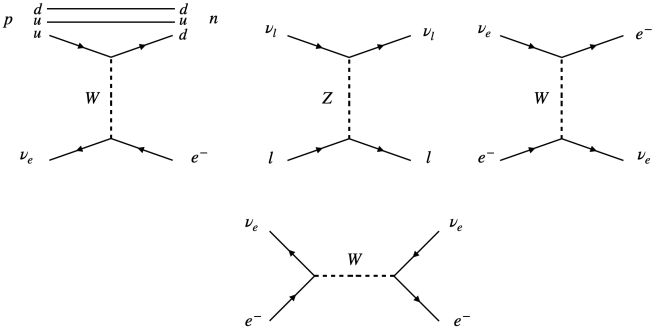

Figure: Inverse beta decay (IBD, top left), neutral current neutrino-lepton scattering (top middle), and charged current neutrino-electron scattering (top right and bottom).

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[1] [Hirata et al., 1987], [Bionta et al., 1987], and [Alexeyev et al., 1988]

Simulated Scintillator Signal

Interaction Channel	# of Events
$\nu_x + p \rightarrow \nu_x + p$	429.1±12.0
$\bar{\nu_e} + p \rightarrow n + e^+$	194.7±1.0
$\bar{\nu_e} +^{12}\text{C} \rightarrow^{12}\text{B} + e^+$	7.0±0.7
$\nu_e +^{12}\text{C} \rightarrow^{12}\text{N} + e^-$	2.7±0.3
$\nu_x +^{12}\text{C} \rightarrow^{12}\text{C}^*(15.1\text{MeV}) + \nu_x'$	43.8±8.7
$\nu_x +^{12}\text{C} \rightarrow^{11}\text{C or }^{11}\text{B} + \text{X}$	2.4±0.5
$\nu_e/\bar{\nu_e} + e^- \rightarrow \nu_e/\bar{\nu_e} + e^-$	13.1

Table: Predicted event rates for 780 tonnes of LAB+PPO (no flavour changing mechanisms included). Adapted from [Andringa et al., 2015].

Model

Detection potential is based upon a supernova at $d = 10$ kpc from Earth which releases 3×10^{53}erg of binding energy evenly among all six neutrino flavours and types. Mean energies are $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu_e}} \rangle = 15$, and $\langle E_{\nu_x} \rangle = 18$ MeV. [Andringa et al., 2015]

Simulated Scintillator Signal

$$\nu_x + p \rightarrow \nu_x + p$$

$$\langle E_{\nu_x} \rangle = 17.8^{+3.5}_{-3.0}(\text{stat.})^{+0.2}_{-0.8}(\text{syst.})\ \text{MeV}$$

$$\langle \varepsilon_{\nu_x} \rangle = (102.5^{+82.3}_{-42.2}(\text{stat.})^{+16.2}_{-13.0}(\text{syst.}))\times 10^{51}\ \text{erg}$$

[Andringa et al., 2015]

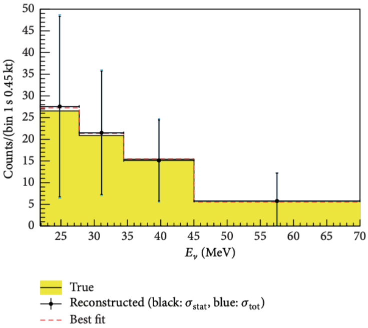


Figure: Time integrated neutrino-proton scattering energy distribution in the first second of a supernova.

SuperNova Early Warning System

- Increases the sensitivity to faint or distant supernovae and the alert confidence; coincident signals may allow for triangulation to the direction of the source
- *SNEWS 2.0*: lower thresholds, integrated multi-messenger approach, pre-core-collapse alert (full details in [Al Kharusi et al., 2021])

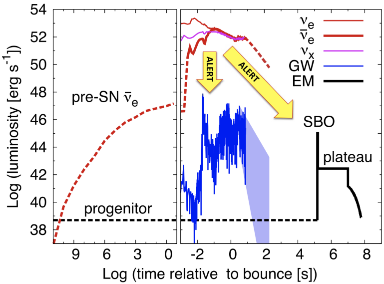


Figure: Multi-messenger signals before and after collapse of a 17 $M_\odot$ progenitor star. [Al Kharusi et al., 2021]

Simulated Water Signal

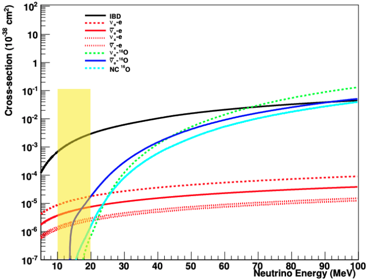


Figure: Cross sections for potential supernova neutrino interaction channels. [Scholberg, 2011]

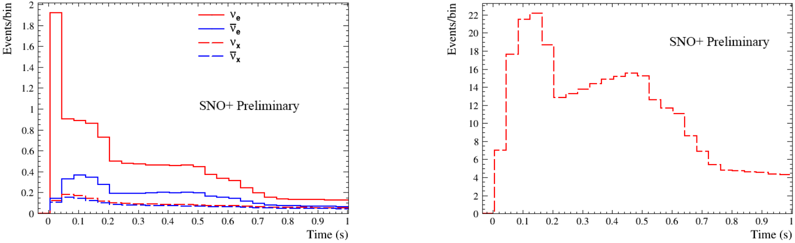
- Volume of UPW between the PSUP and the AV acts as an additional water Cherenkov detector (2.12 kT)
- Sensitive to inverse beta decay (IBD) and elastic scattering off of electrons

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

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

- Scattered electrons are sensitive to the incoming neutrino direction, and could potentially be used for obtaining directional information that is difficult in scintillator

Simulated Water Signal



Truth (MC) event counts for the external volume (EV) of SNO+ for the first second of a supernova at $d = 10$ kpc from Earth. Only elastic electron scattering (left) and IBD (right) events were simulated in this case (IBD events were only generated from $\bar{\nu}_e$ interactions).

Water Pointing

$$\cos(\theta_{SN}) = \frac{\hat{x}_R \cdot \hat{x}_{SN}}{|\hat{x}_R||\hat{x}_{SN}|}$$

$\hat{x}_{SN} = (+1.0, 0.0, 0.0)$

$\hat{x}_R$: Reconstructed direction

- Total of 60 supernova simulations at $d = 10$ kpc for a 2 s time window
- Includes only the electron elastic scattering events (induced by all flavours)

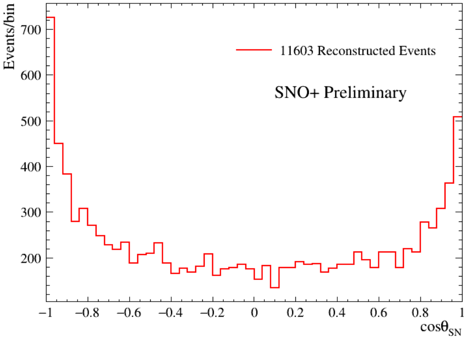
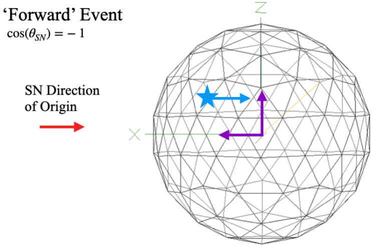
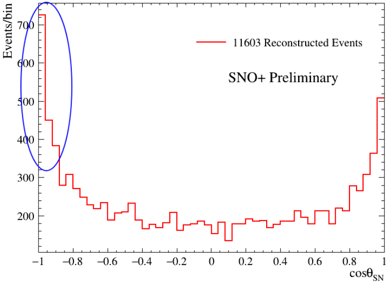


Figure: Angular distribution of the reconstructed events in the SNO+ EV.

Water Pointing

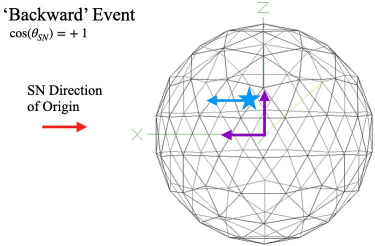




Forward peaking events have reconstructed directions aligned with the supernova origin direction, pointing away from the source.

Figure: Angular distribution of the reconstructed events in the SNO+ EV.

Water Pointing



Backward peaking events have reconstructed directions pointing towards the supernova origin direction.

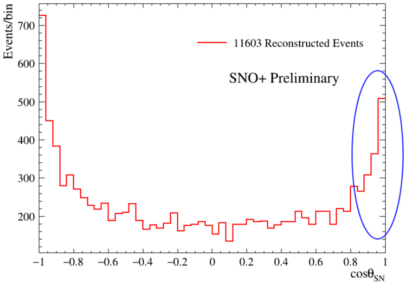


Figure: Angular distribution of the reconstructed events in the SNO+ EV.

This population of events is unexpected (and not observed in the solar pointing in SNO+ water phase) and still under investigation.

Conclusion

Now in full scintillator phase, SNO+ has the capability to be sensitive to supernova neutrinos through multiple channels.

Neutral current neutrino-proton scattering could measure the flux of ν_x.

The external volume of water has the potential to act as a secondary Cherenkov detector to quickly estimate the direction of an incoming supernova event.

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Questions? Comments?

Muon Flux

The muon rate for SNOLab is measured at 0.286 ± 0.009 μ/m^2/day for 6010 m.w.e. of shielding. [Aharmim et al., 2009]

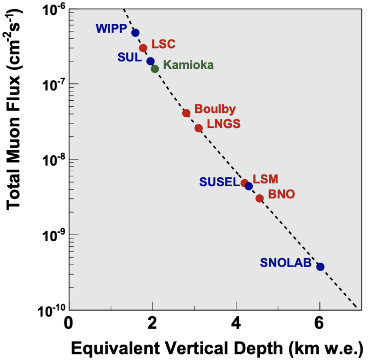

Figure: [Gómez-Cadenas et al., 2011]

^{130}Te

^{130}Te has the highest natural abundance of all favoured $0\nu\beta\beta$ candidates, as well as a long $2\nu\beta\beta$ decay half-life. It's Q-value falls below the two highest backgrounds, necessitating stringent radio purity.

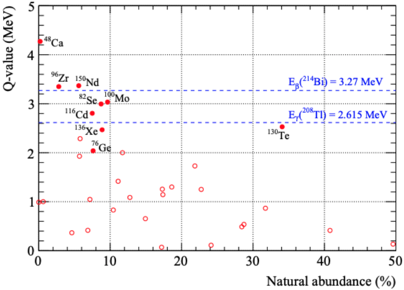

Figure: Q-value vs. abundance of isotopes capable of $2\nu\beta\beta$ decay. [Albanese et al., 2021]

Chandrasekhar Limit

$$M_{Ch} = 5.83 Y_e^2 \tag{1}$$

where Y_e is the number density of electrons relative to the total nucleon number density,

$$Y_e = \frac{n_e}{\rho N_A}. \tag{2}$$

For $Y_e = 0.50, M_{Ch} = 1.457 M_\odot$. As the number of electrons is depleted in the core, the Chandrasekhar mass limit decreases accordingly. [Woosley et al., 2002]

Neutrino Generation

1. **Electron Capture:** $e^- + p \rightarrow n + \nu_e$; emitted neutrino has a characteristic energy, and a recoil is caused in the daughter atom with characteristic momentum. Daughter atom will de-excited into the ground state by a gamma ray or internal conversion.
2. **Beta Minus Decay:** $n \rightarrow p + e^- + \bar{\nu}_e$; radioactive decay of a neutron which emits a beta particle and an electron anti-neutrino.
3. **Weak Process Pair Annihilation**: $e^+ + e^- \rightarrow \nu + \bar{\nu}$; occurs in the high density region of neutrinos trapped by the in-fall of matter in the accretion phase, where thermal photons create the electron-positron pairs.

Neutrino Emission Epochs

Epoch	Duration	Dominant Emission
Pre-supernova	days	$\bar{\nu}_e$
Collapse	$<$ 50 ms	ν_e
Accretion	$\simeq$ 100 ms (ONeMg core)	$\nu_x < \bar{\nu}_e < \nu_e$
	$\simeq$ 200-700 ms (Fe core)	$\nu_x < \bar{\nu}_e < \nu_e$
Cooling	$\simeq$ 10 s	all flavours

Table: Summary of neutrino emission during different supernova phases. Table adapted from [Horiuchi and Kneller, 2018].

SNEWS Detector Types

Type	Material	Capability			Flavour
		Energy	Timing	Pointing	
Scintillator	C,H	true	true	false	$\bar{\nu}_e$
Water Cherenkov	H_2O	true	true	true	$n\bar{u}_e$
Heavy Water (NC)	D_2O	false	true	false	ν_e
Heavy Water (CC)	D_2O	true	true	true	ν_e,$\bar{\nu}_e$
Liquid Argon	Ar	true	true	true	ν_e
High Z/Neutron	Pb, Fe	true	true	false	all
Radio-Chemical	^{37}Cl, ^{127}I, ^{71}Ga	false	false	false	ν_e

Table: Types of supernova neutrino detectors and their capabilities. Table adapted from [Pietro et al., 2004].