Exploring Supernovae with SNO+ and HALO-1kT

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SN Neutrino Modeling

- Study sensitivities of two detectors: SNO+ and HALO-1kT
- Use power law spectrum[1] for neutrino fluence at detector:

$$\frac{d\Phi_\alpha}{dE} = \frac{1}{4\pi d^2} \frac{\epsilon_\alpha}{\langle E_\alpha \rangle} \frac{(1+\beta_\alpha)^{1+\beta\alpha}}{\Gamma(1+\beta_\alpha)} \frac{E^{\beta_\alpha}}{\langle E_\alpha \rangle^{\beta_\alpha+1}} \exp\left[-(\beta_\alpha+1)\frac{E}{\langle E_\alpha \rangle}\right]$$

- Vary parameters to represent different SNe, SN phases
- Adjust distance d, total energy ϵ_α, average energy $\langle E_\alpha \rangle$, and shaping parameter β
- Parameter ranges[2]:
  - $d \leq$ 30 kpc (dia. of Milky Way)
  - $\epsilon_\alpha = \mathcal{O}(10^{52})$ erg each flavour
  - $\langle E_{\nu_\alpha} \rangle \in$ [10, 25] MeV
  - $\beta_\alpha \in$ [2, 5]
- Include oscillations in future work

[1] Keil M T, Raffelt G G, Janka H-T 2003 *Astropart. J.* **590**:2 972

[2] Väänänen D, Volpe C 2011 *J. Cosmol. Astropart. Phys.* **2011**:10 19

Detectors: SNO+

- SNO detector + upgrades
- At SNOLAB, Canada
- Urylon-lined rock cavern
- ultrapure water (UPW) shielding:
  - 5300 tons (outer)
  - 1700 tons (inner)
- ∼9500 PMTs, 54 % coverage
- 12 m dia. acrylic vessel containing:
  - 900 tonnes UPW
  - 780 tonnes liquid scintillator (LS)
  - 780 tonnes LS + 3.0 tonnes ^{nat}Te

Sensitive to galactic SN neutrinos all phases + calibrations

Detectors: SNO+

Interactions[1,2]

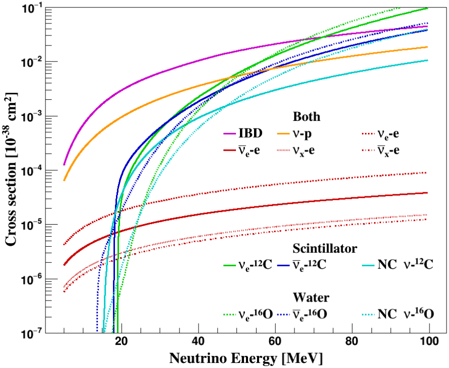


Figure 1: Relevant cross sections in UPW and LS phases of SNO+

- IBD sensitivity ($\bar{\nu}_e$) all phases
- ν-p ES sensitivity (all flavours) during LS loading - (longest phases)
- IBD in LS tagged via 2.2 MeV $\gamma \rightarrow$ assume 100% efficiency
- 17% detection efficiency of $\nu-$p ES (5 m fiducial radius + 200 keVee threshold)

[1] ν-p ES cross section: Beacom J F, Farr W M, Vogel P 2002 *Phys. Rev. D* **66** 033001

[2] All others: See sources from Beck A *et al* 2013 SNOwGLoBES: SuperNova Observatories with GLoBES: Draft, unpublished.

Detectors: HALO

- First generation (HALO)
  - SNOLAB, Canada
  - 79 tonnes lead
  - 370 m of ^{3}He
  - 28% neutron detection efficiency
- Second generation (HALO-1kT)
  - Proposed location: LNGS, Italy
  - 1 kt lead
  - 50% neutron detection efficiency
- Advantages
  - Dedicated SN detector; “Astronomically Patient”
  - Unique vs. all other SN detectors

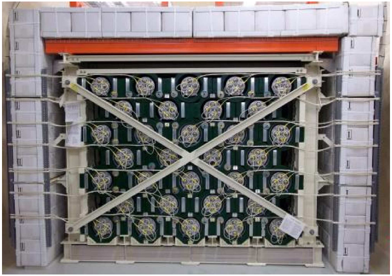


Figure 2: HALO at SNOLAB, CA

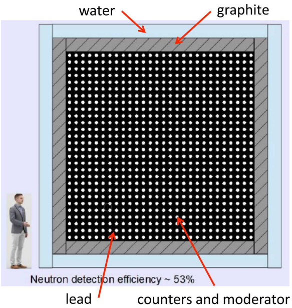


Figure 3: HALO-1kT Concept Design

Detectors: HALO-1kT

Interactions[1]

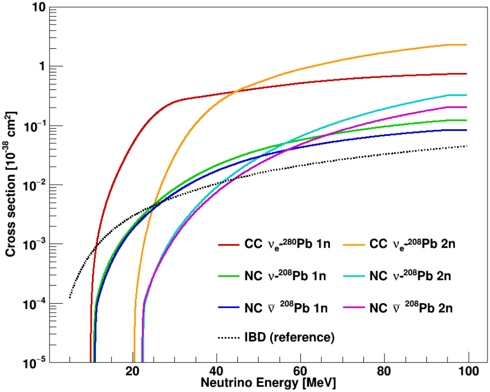


Figure 4: Relevant cross sections in lead for HALO

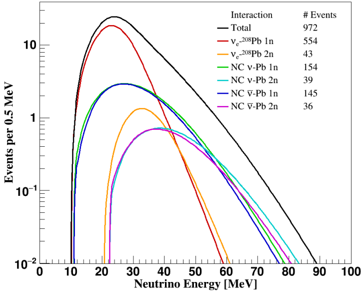
- High ν_e cross sections, ν_e dominated interactions
- Ratio of 1n vs. 2n emission leads to $\langle E_{\nu_e} \rangle$
- Looking into other cross sections (may be a factor of 10 lower than these)

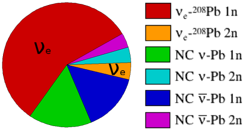
[1] Engel J, McLaughlin G C, Volpe C 2003 *Phys. Rev. D* **67** 013005

Generating events in HALO-1kT and SNO+

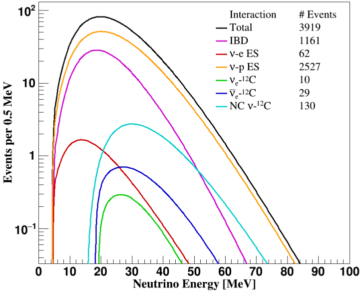
Use SNOwGLoBES software package[1] to generate events

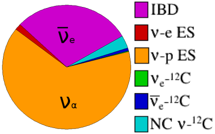
HALO-1kT (1 kt lead)





SNO+ (780 t LS)



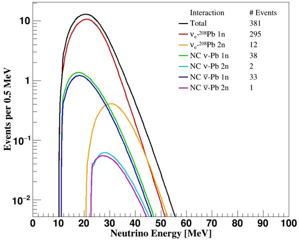


SN ν fluence: d =10 kpc, $\beta = 3$, $\epsilon_\alpha = 5\times10^{52}$ erg (each flavour), with $\langle E_{\nu_e}\rangle = 12$ MeV, $\langle E_{\bar{\nu}_e}\rangle = 15$ MeV, $\langle E_{\nu_x}\rangle = 18$ MeV, no oscillations

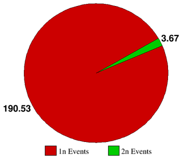
[1] Beck A *et al* 2013 SNOwGLoBES: SuperNova Observatories with GLoBES: Draft, unpublished

Observing Interactions in HALO-1kT: Average Energies

$\langle E_\nu \rangle = 10$ MeV

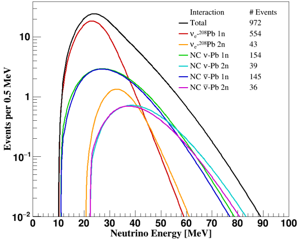


(a) True interactions

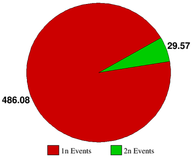


(b) Observed emission

$\langle E_{\nu_e} \rangle = 12$ MeV,
$\langle E_{\bar{\nu}_e} \rangle = 15$ MeV,
$\langle E_{\nu_x} \rangle = 18$ MeV

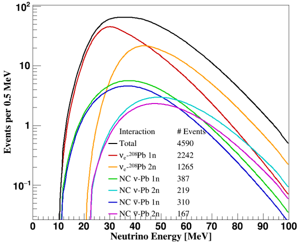


(a) True interactions

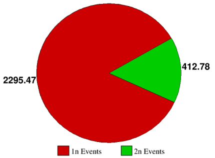


(b) Observed emison

$\langle E_\nu \rangle = 25$ MeV



(a) True interactions

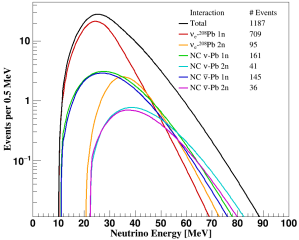


(b) Observed emison

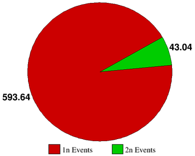
Observed events use a neutron detection efficiency of 0.5

Observing Interactions in HALO-1kT: Shaping Parameters

$\beta_{\nu_e} = 2$

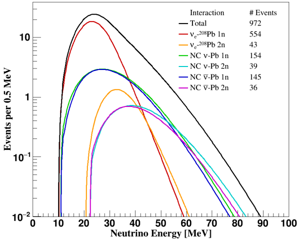


(a) True interactions

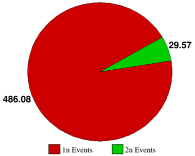


(b) Observed emission

$\beta_{\nu_e} = 3$

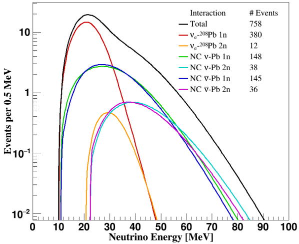


(a) True interactions

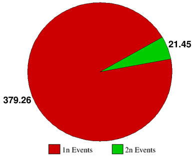


(b) Observed emission

$\beta_{\nu_e} = 5$



(a) True interactions

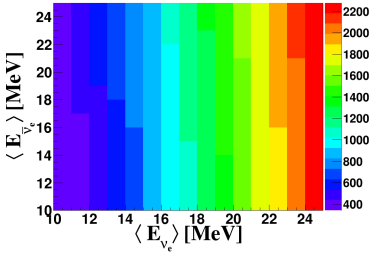


(b) Observed emission

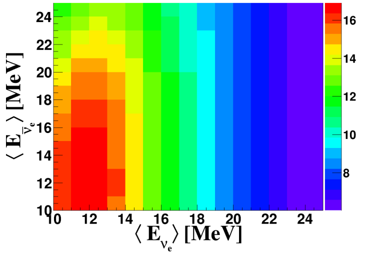
Neutron detection efficiency = 0.5. SN fluence: $d =$10 kpc, $\beta_{\nu_x,\bar{\nu}_e} = 3$, $\epsilon_\alpha = 5\times10^{52}$ erg, $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV, $\langle E_{\nu_x} \rangle = 18$ MeV, no oscillations

Observed Event Ratios, $\langle E_{\nu_x} \rangle = 18$ MeV

HALO-1kT (1 kt lead)

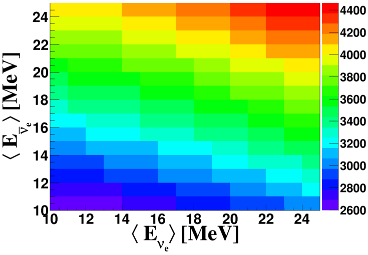


(a) Total number observed neutron events

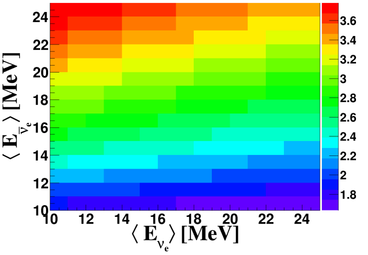


(b) Ratio of 1n/2n events

SNO+ (780 t LS)



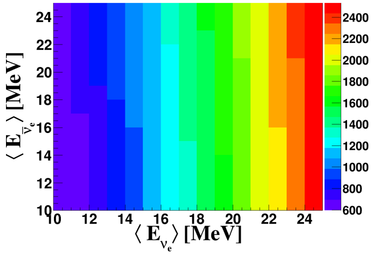
(a) Total number observed events



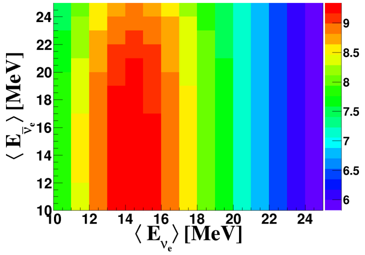
(b) Ratio of IBD/$\nu - p$ ES events

Observed Event Ratios, $\langle E_{\nu_x} \rangle = 25$ MeV

HALO-1kT (1 kt lead)

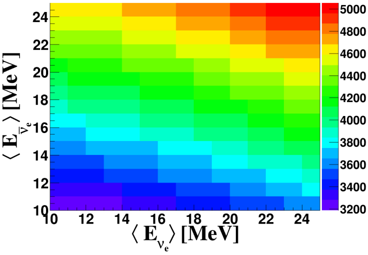


(a) Total number observed neutron events

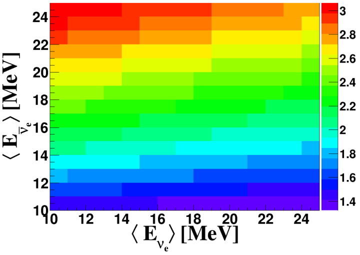


(b) Ratio of 1n/2n events

SNO+ (780 t LS)



(a) Total number observed events



(b) Ratio of IBD/$\nu - p$ ES events

Conclusions

- This talk just hits the tip of the iceberg
- Quantitative analysis to come
- Need to:
  - Incorporate oscillations
  - Constrain $\langle E^0_{\nu_e} \rangle \leq \langle E^0_{\bar{\nu}_e} \rangle \leq \langle E^0_{\nu_x} \rangle$ at neutrinospheres
- SNO+ and HALO-1kT are complementary SN ν detectors
- SNO+ strength: IBD ($\bar{\nu}_e$), $\nu - p$ ES (ν)
- HALO-1kt strength: 1n, 2n emission (ν_e)
- SNO+ and HALO-1kT: Hybrid method for ν mass hierarchy, ν_x spectral study

Thank you!