HALO-1kT – A Massive Helium And Lead Observatory for Supernova Neutrinos with High Sensitivity to ν_e.

Funded in Canada by

Barry Pointon for the HALO-1kT Collaboration

The Many Flavours of Supernova Neutrinos

Neutrino emission from core-collapse supernovae (SNe) is expected to be shaped by a rich combination of astrophysical processes and particle physics. These impact the fluence rates of the neutrino flavours differently during the burst, accretion and cooling phases. Modern SN models predict that neutrinos of different flavours will have different luminosities, average energies and spectral shape parameters, as shown in **Figure 1**.

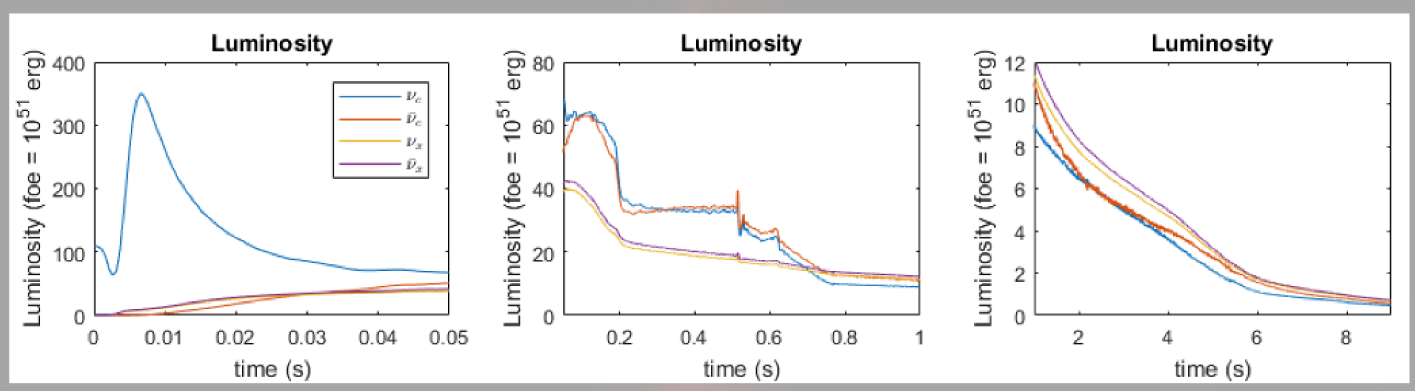

Figure 1. The luminosity of different neutrino flavors as a function of time for the Garching model 'ls200-s27' [Gar].

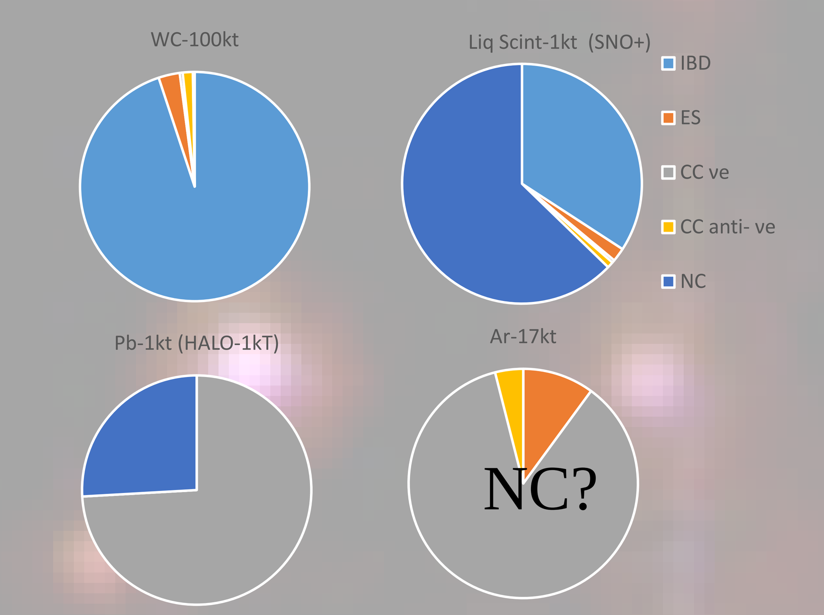

Figure 2. Calculated relative flavor sensitivities for different detector technologies to SN neutrinos based on given SN fluences and detector efficiency parameters. (Courtesy J. Rumleskie).

The majority of operational and planned neutrino detectors are most sensitive to $\bar{\nu}_e$ through charged-current (CC) inverse beta decay (IBD) on hydrogen or neutral-current (NC) interactions with nuclei or neutrino-electron elastic scattering (ES), as shown in **Figure 2**.

However, **lead-based neutrino detectors** have high ν_e sensitivity because the large excess of neutrons in ^{208}Pb effectively Pauli blocks p→n transitions. Argon-based detectors also have high ν_e sensitivity but the relative NC contribution is not well known.

Extracting the maximal physics information from the next galactic supernova(e) requires measuring the signals of multiple neutrino *flavours*.

Lead-based Supernova Neutrino Detection

Neutrino interactions in lead-based detectors proceed by the following CC and NC reactions for the emission of one or two neutrons with cross-sections as shown in Figure 3:

CC: $^{208}\mathrm{Pb}(\nu_e, e^-)^{208}\mathrm{Bi}^* \rightarrow {}^{207}\mathrm{Bi} + 1\mathrm{n}$ $\quad (E_{th} = 10.3\ \mathrm{MeV})$
CC: $^{208}\mathrm{Pb}(\nu_e, e^-)^{208}\mathrm{Bi}^* \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n}$ $\quad (E_{th} = 18.4\ \mathrm{MeV})$
NC: $^{208}\mathrm{Pb}(\nu_x, \nu_x)^{208}\mathrm{Pb}^* \rightarrow {}^{207}\mathrm{Pb} + 1\mathrm{n}$ $\quad (E_{th} = 7.4\ \mathrm{MeV})$
NC: $^{208}\mathrm{Pb}(\nu_x, \nu_x)^{208}\mathrm{Pb}^* \rightarrow {}^{206}\mathrm{Pb} + 2\mathrm{n}$ $\quad (E_{th} = 14.1\ \mathrm{MeV})$

These cross sections are high compared to IBD, however the threshold energies are higher.

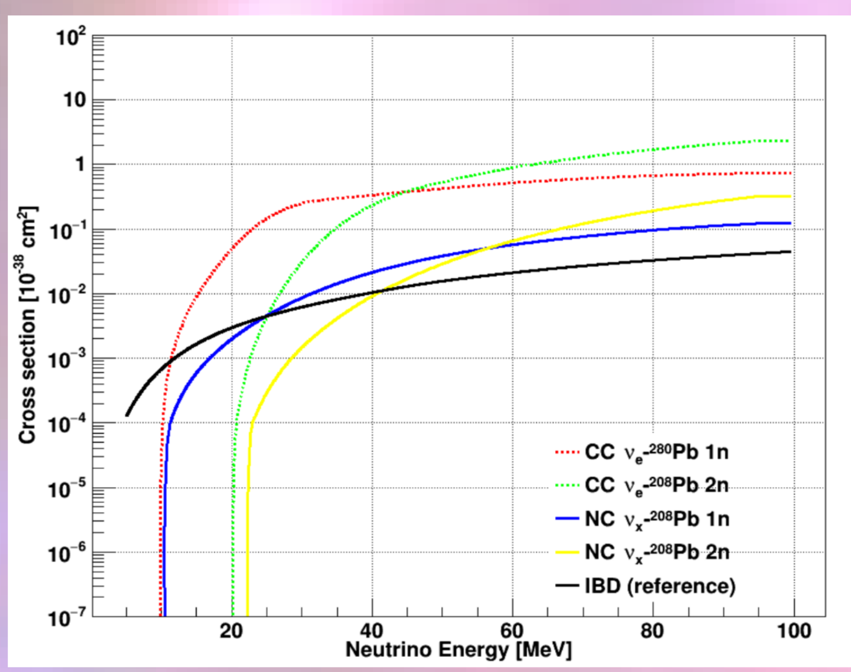

Figure 3. CC- and NC ν – Pb cross sections for the emission of one or two neutrons as a function of neutrino energy. For reference the Inverse Beta Decay cross sections is also shown. From SNOwGLoBES [Bec13]

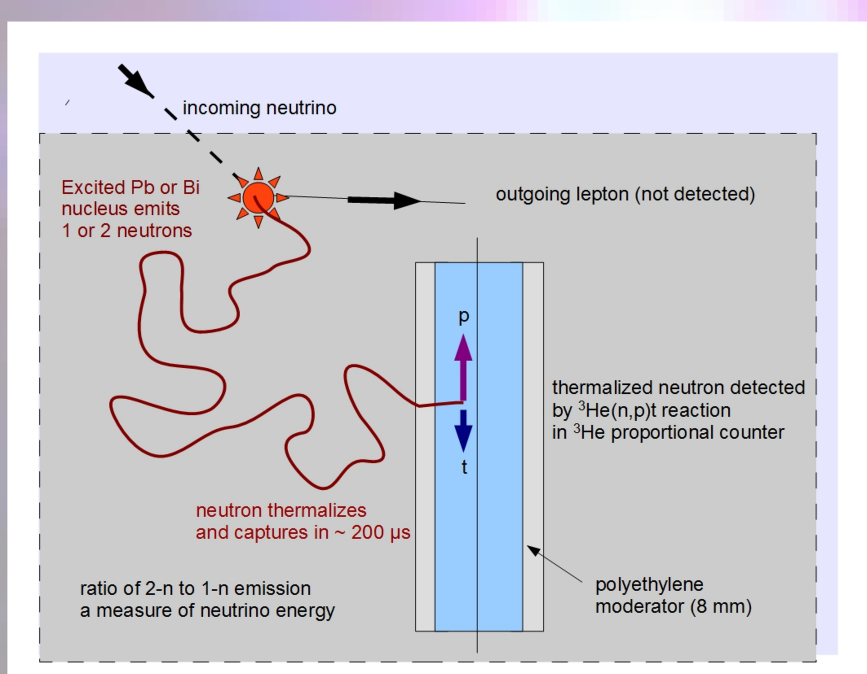

Figure 4. The HALO principle of detecting neutrino interactions in lead by detecting the one or two emitted neutrons in a 3He neutron counter.

Although the electrons from the CC reactions are not easily detected in solid lead, the *neutrons* from CC and NC reactions travel some distance through the lead and may be detected in a ^{3}He proportional counter, as shown in **Figure 4**.

The different thresholds and cross sections for these reactions means that the relative number of 1n and 2n events is sensitive to the average neutrino energy and the shape of the spectrum.

The principle of detecting neutrons from neutrino interactions in lead is used in the Helium and Lead Observatory (HALO) supernova neutrino detector operating at SNOLAB since 2010. HALO uses the original SNO ^{3}He neutron counters to instrument a 79 tonne lead detection volume. The low background of these counters permits sufficient trigger discrimination to allow HALO to be used in the SNEWS network. HALO's simple design minimizes the maintenance requirements so that the detector could have a decades-long SN search.

However, HALO's small mass limits the number of neutrino interactions and the reduces the efficiency for stopping the neutrons in the detector body. These effectively reduce the ability of HALO to study SN at distances > 5 kpc.

HALO-1kT

The decommissioning of the OPERA experiment at LNGS has made available over 1000 tonnes of low activity lead, providing an opportunity to build a much larger lead-based, dedicated SN neutrino detector, HALO-1kT. It will use the HALO principles and be built at LNGS, co-located with the LVD liquid scintillator (LS) detector, to give multi-flavor neutrino sensitivity at one site, and negate the earth oscillation effects between the detectors.

Significant R&D and design work on HALO-1kT is underway:

- New ^{3}He neutron counters are under development. The original SNO neutron counters required an expensive and elaborate manufacturing process to achieve the necessary low backgrounds. While HALO-1kT has less stringent specifications, the SNEWS trigger requires reducing the background counts due to the U and Th decay chains in the detector body bulk and the Rn decay chain on the inner surface. Modifications to commercial detector bodies, including using Cu plating, are being investigated.

- Monte Carlo simulations are being used to guide the overall detector configuration with respect to the number, positioning and spacing of the counters, the moderator design and He gas filling. As well, the design of an external Graphite neutron reflector and shielding from external neutrons is being optimized. The current conceptual design in shown in **Figure 5**.

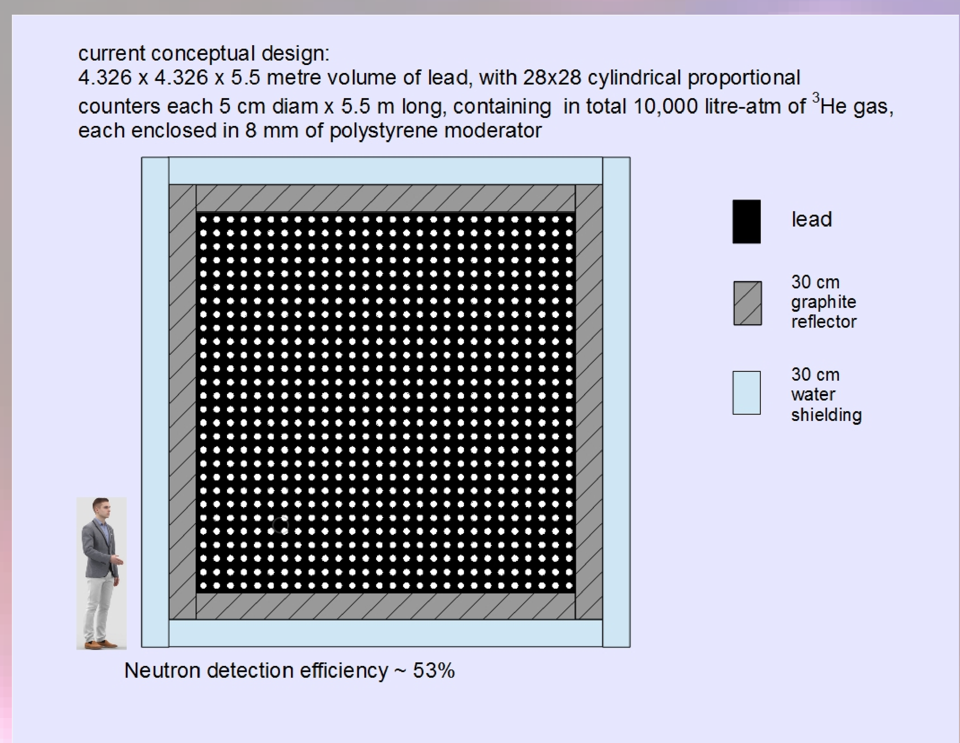

Figure 5. Flavor sensitivities for different detector technologies.

The design must be optimized to produce the highest one and two neutron counting efficiency while minimizing the number of detectors and amount of critical materials. Presently, the modeled 1n efficiency is ~ 53% for using a 28 x 28 array of detectors with a total of 10,000 litre-atm of ^{3}He.

- Modeling of the expected detector signal and physics extraction is underway. Some methods and results are presented in "Data Unfolding for the Helium and Lead Observatory" (J. F. Crenshaw – Poster #228).
- A very preliminary analysis suggests that by comparing the ν_e , Pb signals measured by HALO-1kT with the measured $\bar{\nu}_e$, IBD signal (e.g. from LVD) may resolve the neutrino mass hierarchy using a method similar to that described in [Val16].

Figure 6 shows that for the SN cooling phase, NMH and IMH produce non-overlapping distributions (at 90% CL) for ratios of LVD (IBD) to HALO-1kT(1n) and LVD (IBD) to HALO-1kT(1n+2n) at 10 kpc. The distributions are even more cleanly separated at closer distances. This shows the potential of HALO-1kT to contribute to resolving the mass hierarchy.

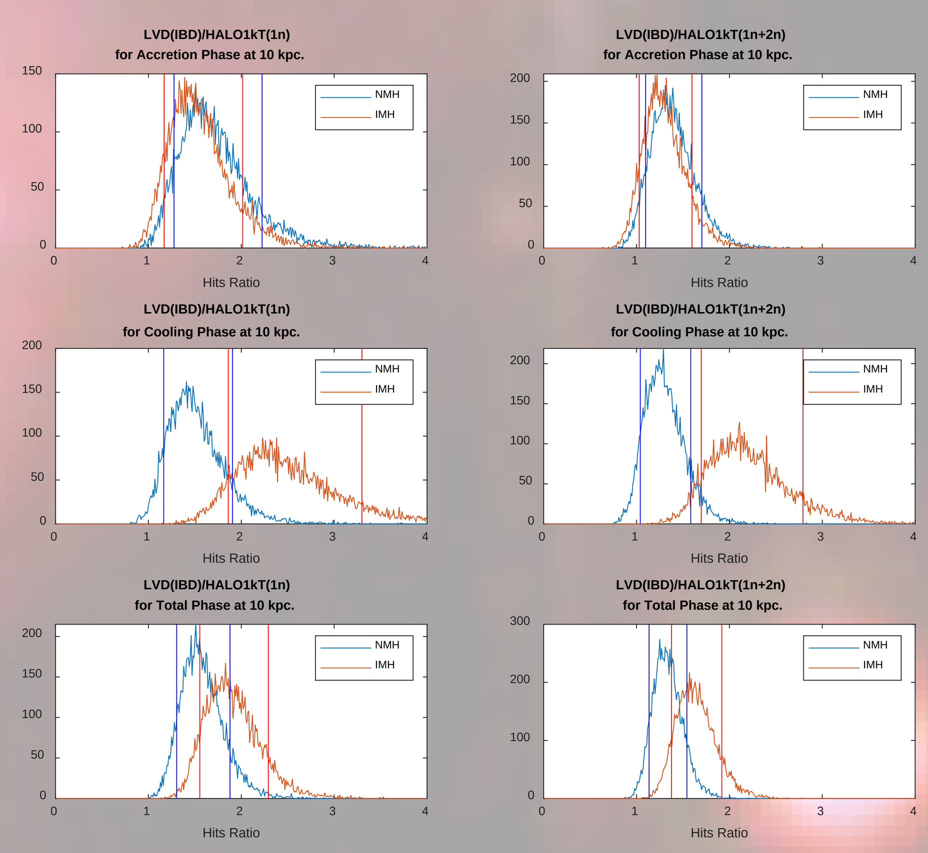

Figure 6. Ratios of LVD IBD events to HALO-1kT 1n, and 1n+2n events from a "toy' Monte Carlo for different phases of the SN neutrino emission at 10 kpc using the Garching model 'ls220-s27' [Gar].

CONCLUSION

Lead-based supernova neutrino detectors have a unique flavour sensitivity that will help characterize the neutrino emission from the next galactic SN and unfold the complex physics hidden within. The greatly increased mass of HALO-1kT would enable it to detect SNe throughout our galaxy. With a dedicate role and a robust and stable design, HALO-1kT could potentially study multiple SNe over its lifetime.

REFERENCES

[Bec13] Beck, A. et al., SNOwGLoBES: SuperNova Observatories with GLoBES: DRAFT, http://www.tapir.caltech.edu/~cott/CGWAS2013/snowglobes_1.1.pdf

[Gar] Data courtesy of H-Thomas Janka and the Garching Group.

retrieved from https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/archive.html,

[Val16] Vale, D. et al., Hybrid method to resolve the neutrino mass hierarchy by supernova (anti)neutrino induced reactions. Journal of Cosmology and Astroparticle Physics 2016 (02), 007.

COLLABORATING INSTITUTIONS

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