Data Unfolding for the Helium and Lead Observatory

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Introduction

The Helium and Lead Observatory (HALO) is a supernova neutrino detector at SNOLAB that has been operational since 2010, and is a member of the SuperNova Early Warning System (SNEWS). The detector consists of 128 ^{3}He counters embedded in a 79-ton lead matrix (Figure 1).

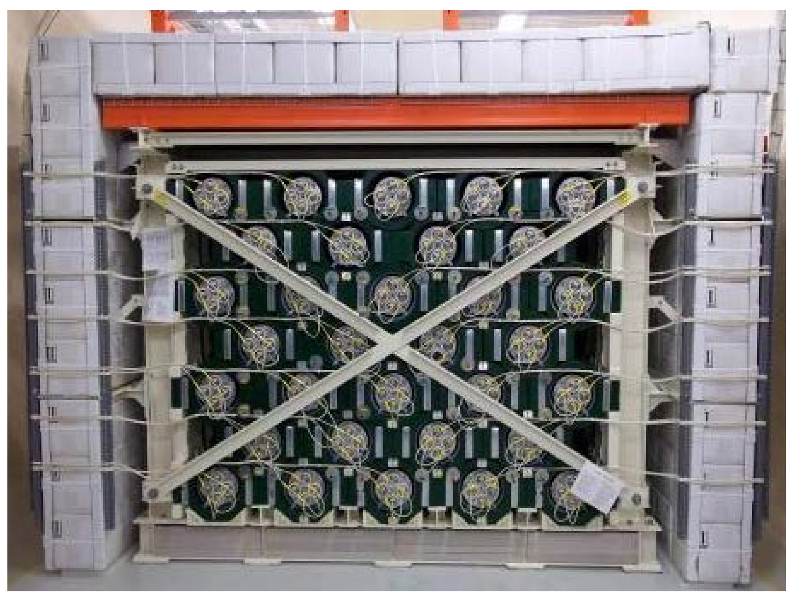

Figure 1. Front view of HALO

Depending on the incident neutrino energy, interactions with lead may generate single (1n) or double (2n) neutron events. The relative rates of 1n and 2n events are sensitive to supernova neutrino spectra. It is therefore important to develop a method for reconstructing true 1n and 2n numbers from detected events.

Expected Event Numbers

Numbers of 1n, 2n events in HALO can be calculated from different supernova neutrino flux models using the SNOwGLoBES software [1].

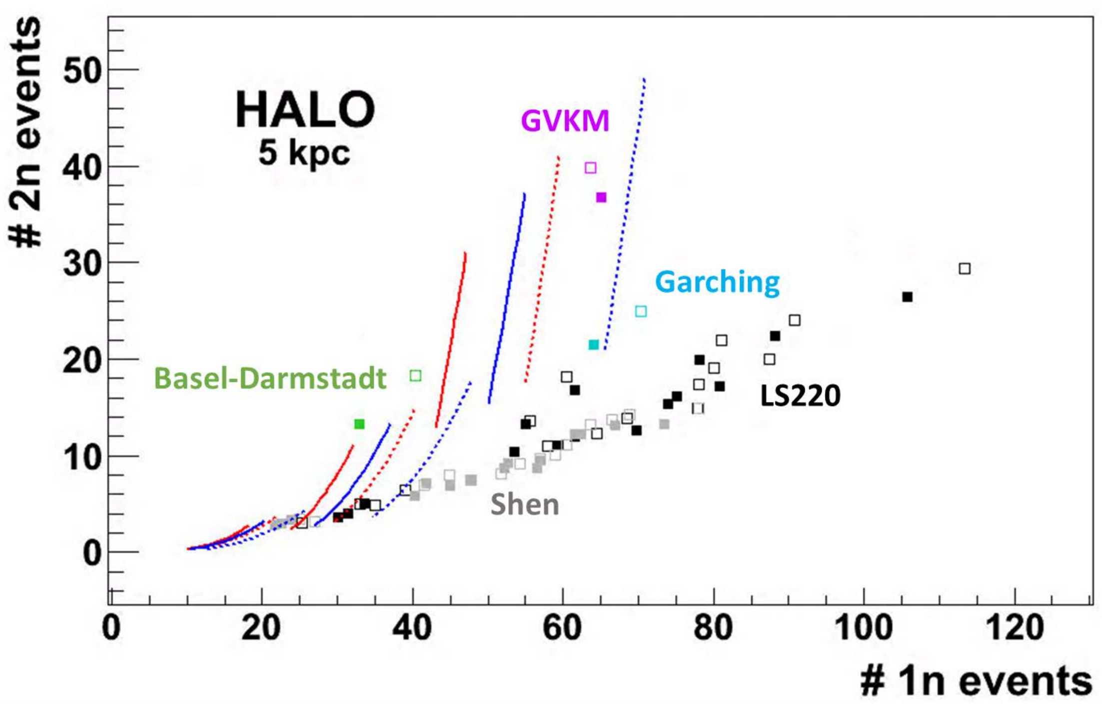

Figure 2. Expected 1n, 2n event numbers in HALO given various neutrino flux models for a supernova at 5kpc. Fluxes for blue and red curves from [2], gray “Shen” and black “LS220” fluxes from [3], green “Basel-Darmstadt” fluxes from [4], pink “GVKM” fluxes from [5], teal “Garching” fluxes from [6].

Simulating Detections

Detection of 1n, 2n events is simulated using a Monte Carlo that incorporates Poisson statistics and the detector efficiencies. The detector efficiencies, determined via Geant4 simulations and by placing a calibrated neutron source within the detector, are summarized by the efficiency matrix:

$$A = \begin{pmatrix} \text{1n measured as 1n} & \text{2n measured as 1n} \\ \text{1n measured as 2n} & \text{2n measured as 2n} \end{pmatrix}$$

$$= \begin{pmatrix} 28.3\% & 37.6\% \\ 0 & 9.7\% \end{pmatrix}$$

Unfolding

Data unfolding must be performed to determine the true number of 1n, 2n events in HALO given the number of detections. A simple unfolding can be performed by inverting the efficiency matrix, but this method results in large uncertainties and unphysical results (Figure 3). A Bayesian unfolding algorithm can improve on these problems.

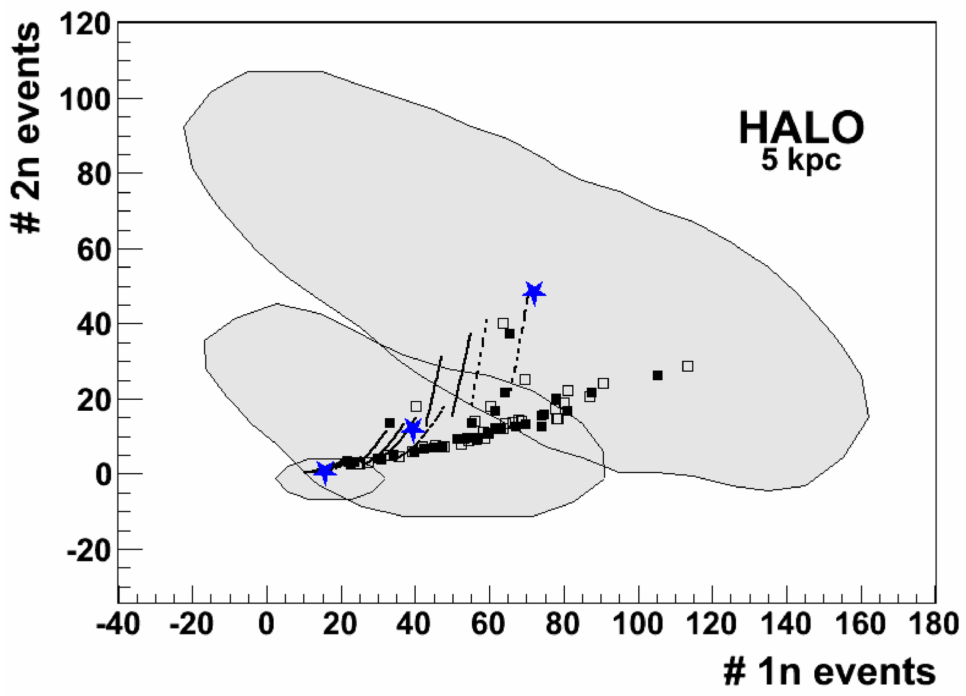

Figure 3. Inverse-matrix unfolding for 3 sample 1n, 2n points. Gray contours contain 90% of unfolded points.

The RooUnfold iterative Bayesian algorithm [7] unfolds by using a prior, which is iteratively updated using the results of the unfolding. This process is iterated until the result converges.

I perform the unfolding with three priors:

(1) a prior that restricts the unfolding to the positive 1n, 2n plane

(2) a prior based on expected 1n, 2n values for an unknown supernova distance

(3) a prior based on expected 1n, 2n values assuming distance is known within 10%

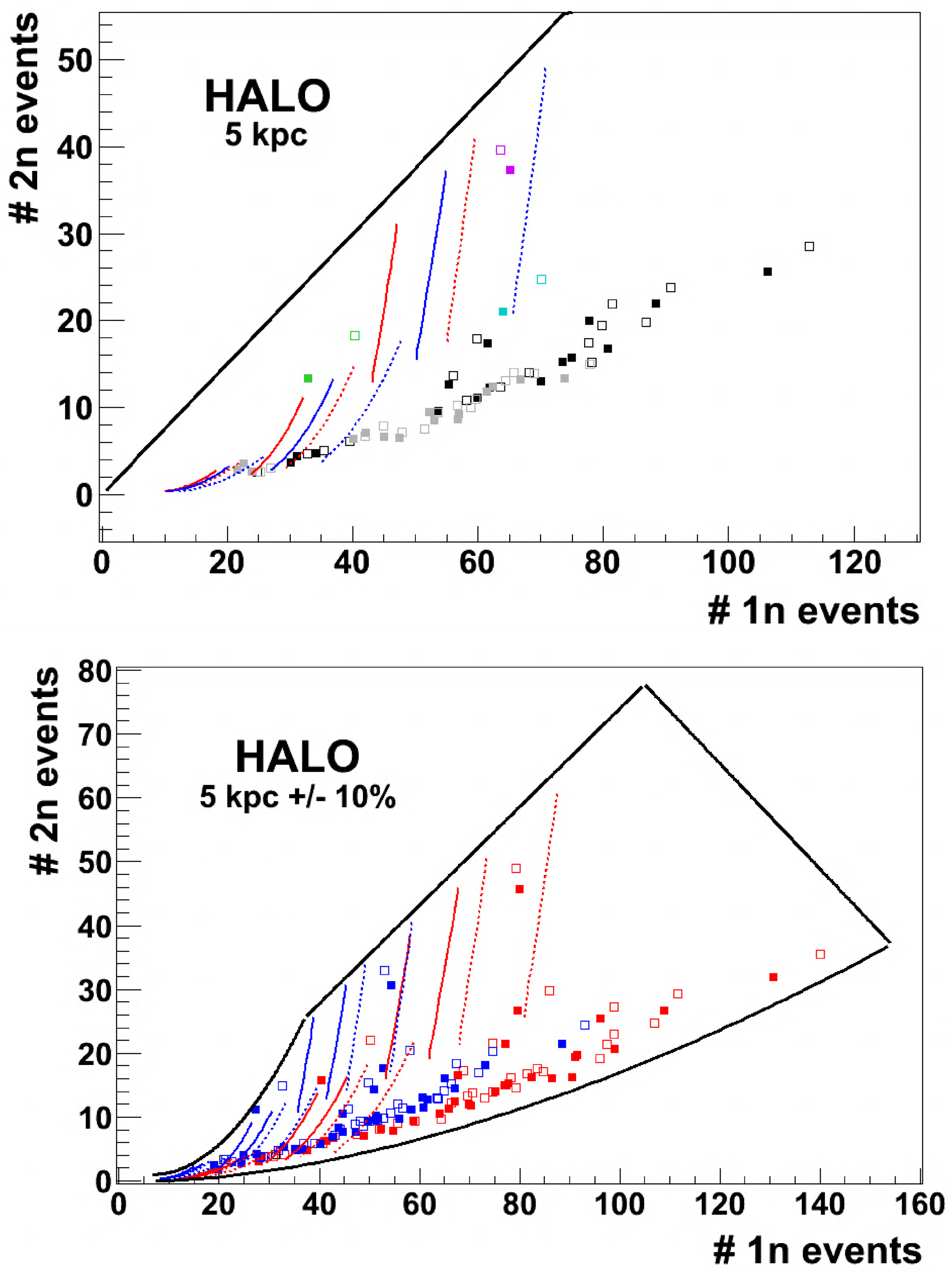

Figure 4. Top: Prior 2 (“distance unknown”). As 1n, 2n pairs scale linearly with distance it is possible to impose a maximum ratio 2n/1n. Bottom: Prior 3 (“distance known”). The data from Figure 2 is plotted twice, for supernovae at 4.5 kpc (red) and 5.5 kpc (blue). An envelope is constructed around the range of points.

Results

Sample 1n, 2n values are simulated then unfolded using the three priors. The process is repeated 10,000 times for each. The results are represented as gray contours, which contain 90% of the unfolded data points. The plots below represent neutrino detections in HALO for a supernova at 5 kpc. Similar plots were also created for a supernova at 10 kpc, and for detections in HALO-1kT, the proposed 1-kiloton upgrade to HALO at LNGS.

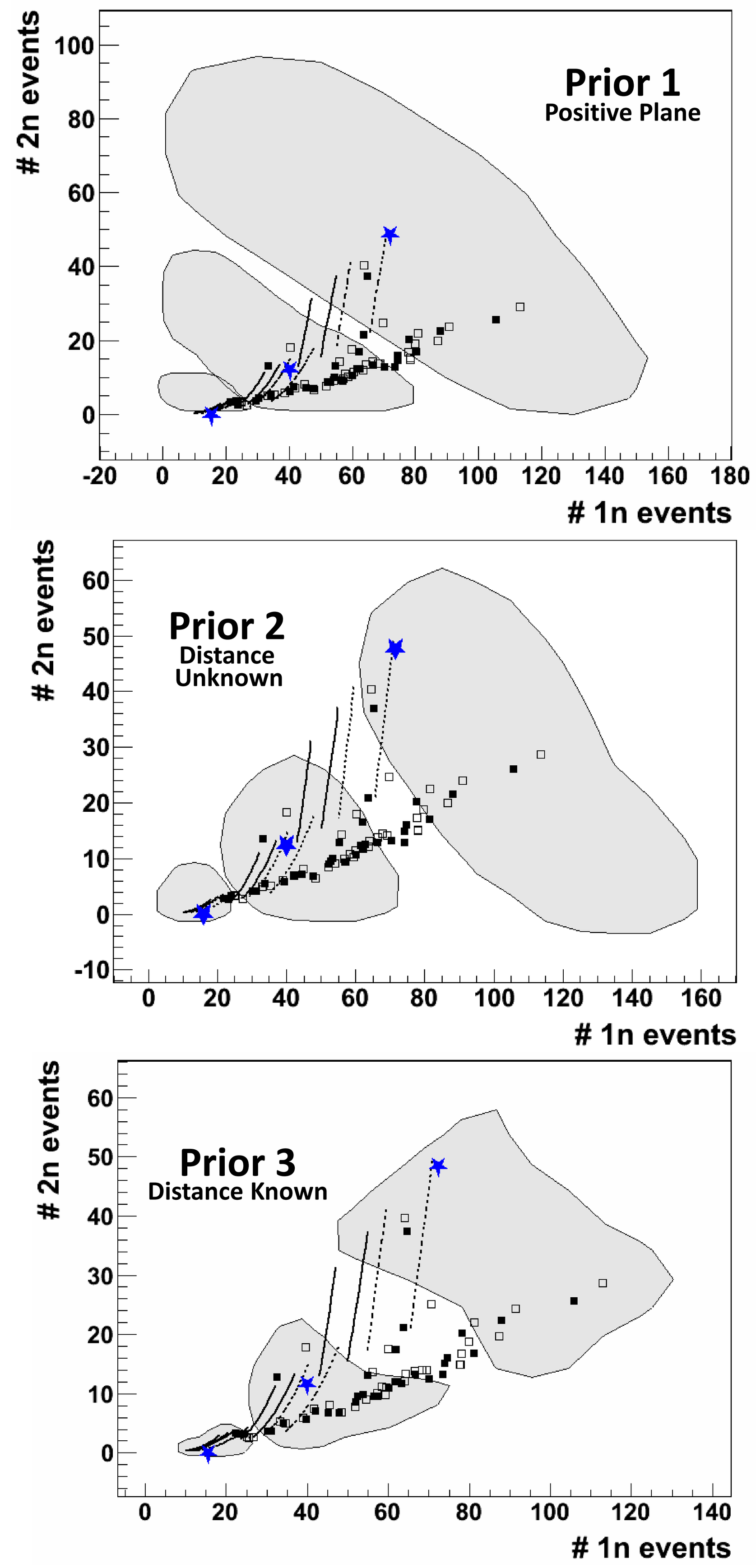

Figure 5. 3 sample 1n, 2n points (represented by stars) for a supernova at 5 kpc are simulated and unfolded using the three priors. Gray contours are drawn around 90% of the unfolded points. The models from Figure 2 are overlaid for reference.

Figure of Merit

The sensitivity of HALO and HALO-1kT decreases with the supernova distance. To quantify this sensitivity, the percentage of reasonable models that is excluded by a contour is plotted as a function of distance.

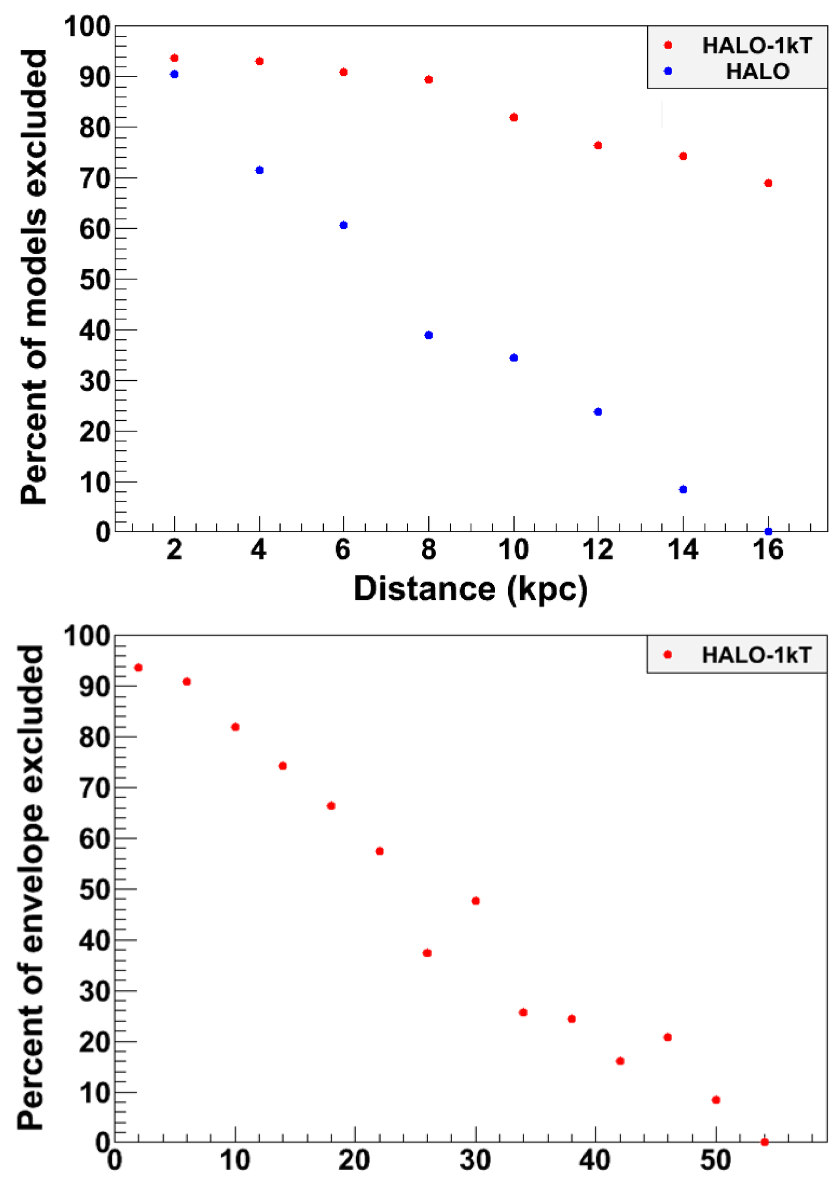

Figure 6. Percent of models excluded by unfolded contour as a function of distance. The “distance known” prior is used. Top: Comparison of HALO and HALO-1kT Bottom: Only HALO-1kT

References

[1] http://www.phy.duke.edu/~schol/snowglobes

[2] Väänänen, D., & Volpe, C. (2011). The neutrino signal at HALO: Learning about the primary supernova neutrino fluxes and neutrino properties.

[3] Huedepohl, L. (2014). Neutrinos from the Formation, Cooling and Black Hole Collapse of Neutron Stars. PhD. Thesis, Technische Universitat Muenchen

[4] Bandyopadhyay et al. (2016). Detecting supernova neutrinos with iron and lead detectors.

[5] Gava et al. (2009). A dynamical collective calculation of supernova neutrino signals.

[6] Hüdepohl et al. (2010). Neutrino signal of electron-capture supernovae from core collapse to cooling.

[7] Adye, T. (2011). Unfolding algorithms and tests using RooUnfold.