# Extracting the time of core bounce from a SN signal in HALO-1kT for implementation into SNEWS 2.0

Remington Hill

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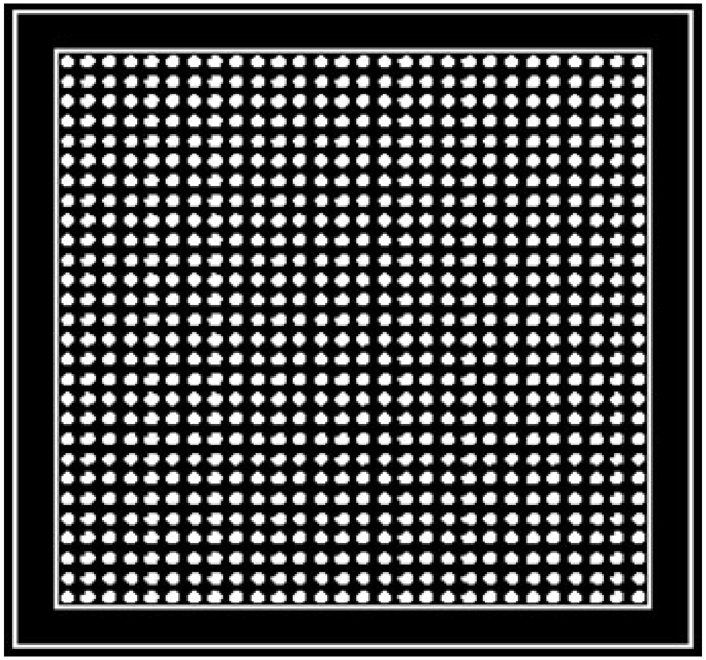
# About me

- MSc student at Laurentian University.
  - Under the supervision of Dr. Clarence Virtue, currently on the HALO-1kT experiment.
  - Previously worked on HALO-1kT (summer 2018) and nEXO (2018-2020).
  - Graduated with a BSc Physics in April 2020.
- What do I do outside work?
  - Cooking (have loved learning all sorts of new recipes).
  - Chess (haven't played in a long time, been nice to get back into it).
  - Reading (just starting Jeff VanderMeer's new book).


Above is a photo of me ~3 years ago at the conclusion of my summer work term. The other two are meals that I had earlier this week (Butter chicken/Naan and a Clubhouse sandwich on homemade bread).

# Outline

- Overview of core-collapse supernovae.
    - Neutrino production and observation at Earth.
- The SuperNova Early Warning System (SNEWS).
    - History and collaboration overview.
- Introduction to the Helium and Lead Observatory (HALO) and HALO-1kT.
    - Experimental design and aims.
- Event generation using the neutrino event calculator SNOwGLoBES.
- Monte Carlo simulation of neutrino signal in lead based detectors (HALO and HALO-1kT).
- Extracting the time of core bounce ($t_0$) from the neutrino signal.
- Future plans.
    - Linear fitting.
    - Implementation into SNO+ and HALO.

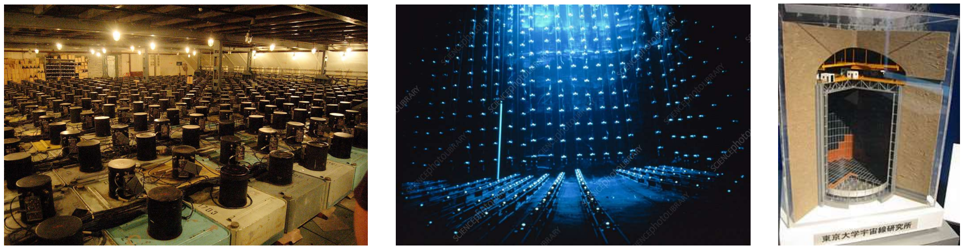


Note: The HALO-1kT experiment as it currently exists in our Geant4 Monte Carlo.

# Core-collapse supernovae (CCSNe)

- Sufficiently massive stars ($\sim 8\ M_{\odot}$) can end their life as core-collapse supernova.
- Layered 'onion' like structure forms.
  - Progressively heavier elements towards core.
- Inert core cannot undergo fusion; if the core is $> 1.4\ M_{\odot}$ (Chandrasekhar limit), can become sufficiently unstable to collapse.
  - No longer supported by $e^-$ degeneracy pressure.
- Core collapses to form protoneutron star (PNS); first neutrinos produced via $\gamma \rightarrow \nu\bar{\nu}$ and $e^- + p \rightarrow n + \nu_e$ (electron capture, EC).
- Material begins collapsing into core, rebounding due to ultra high densities.
  - Moment of core bounce defined as $t_0$.
  - Neutrinos drive the rebounded material outward.
  - Formation of three discrete neutrinospheres.
- Optical signal blocked until shock breakout.

Courtesy of European Southern Observatory

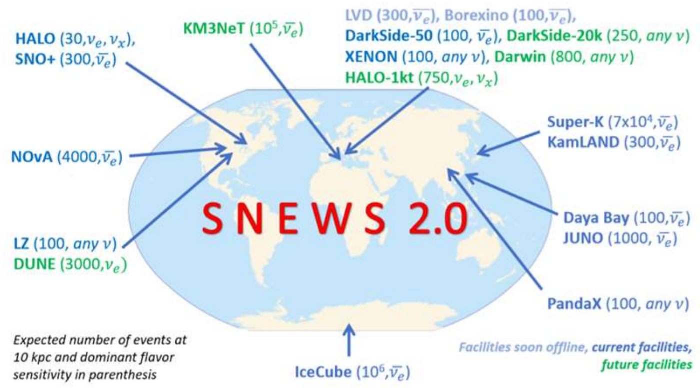


Baksan (BUST, left), IMB (middle) and Kamiokande-II (right)

# SNEWS 2.0

- SNEWS Formed in the late 90's, operating since 2005.
- Purpose is to coordinate response to $\nu$ signal in multiple $\nu$ detectors.
  - Alerts, triangulation, etc.
- As of 2019, there are 7 experiments participating in SNEWS (right).
  - Many more will come online (or join) soon.
  - Not only neutrino experiments but dark matter detectors such as PandaX or Darwin.
- Intent is to expand SNEWS into the Mutli-Messenger Astronomy (MMA) era.
  - Bring in gravitational wave detectors, optical instruments, theorists, etc.
- SNEWS 2.0 aims will:
  - Reduce tolerances (no longer "once in my lifetime").
  - Improve triangulation (next-generation detectors greatly increase statistics).
    - NSF grant application proposed extracting $t_0$ from neutrino fluxes.
    - Each experiment would communicate with the SNEWS 2.0 server the extracted $t_0$ and its associated uncertainty.

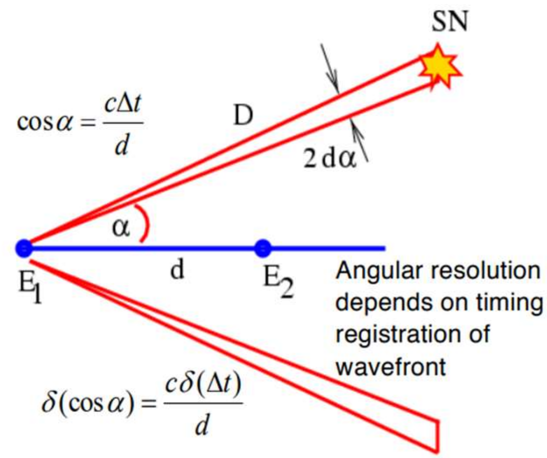

SNEWS – List of experiments that joined SNEWS over the past 15 years.



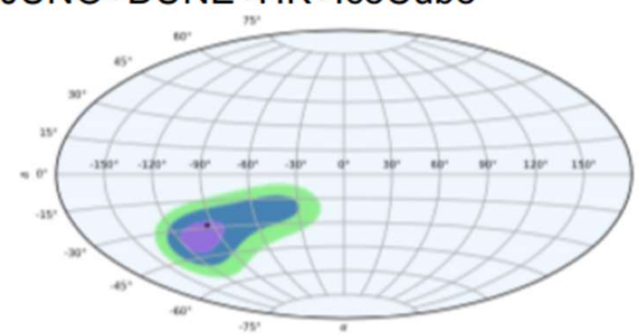

SNEWS 2.0 - Experiments currently online and those coming online soon.

# Triangulation with SN neutrinos

- The idea of triangulating to a SN with neutrinos is not new.
  - Can a supernova be located by its neutrinos? [J. F. Beacom & P. Vogel Phys. Rev. D60 (1999) 033007]
  - At the time, deemed unrealistic.
    - Not enough statistics.
    - Cannot get good timing between experiments (ms, ideally 100s of us).
- Current and next-generation detectors have sufficient statistics to triangulate to core-collapse SN.
  - SNO+, JUNO, DUNE, HyperK, IceCube, etc.
- Studies have been conducted on the precision of triangulation in next generation detectors.
  - N.B. Linzer & K. Scholberg, arXiv:1909.03151v1 [astro-ph.IM] (2019).
  - A. Coleiro et al., arXiv:2003.04864v1 [astro-ph.HE] (2020).
- The techniques devised in these studies are not possible in HALO, we will need to devise an alternative.
  - What is HALO? And its bigger brother HALO-1kT?




JUNO+DUNE+HK+IceCube

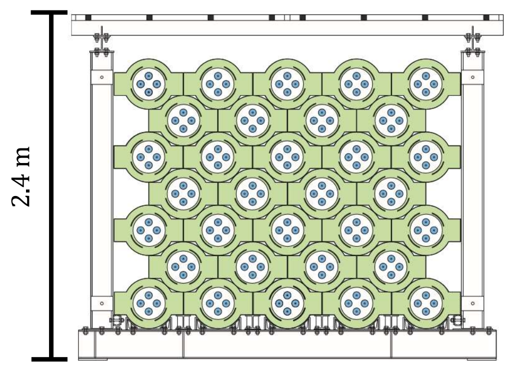


Courtesy of N. B. Linzer and K. Scholberg.
$1\sigma$, $2\sigma$ and $3\sigma$ region for SN triagulated from the 4 detectors listed above (Garching model @ 10 kpc, NO, $\Delta t$ of first events).

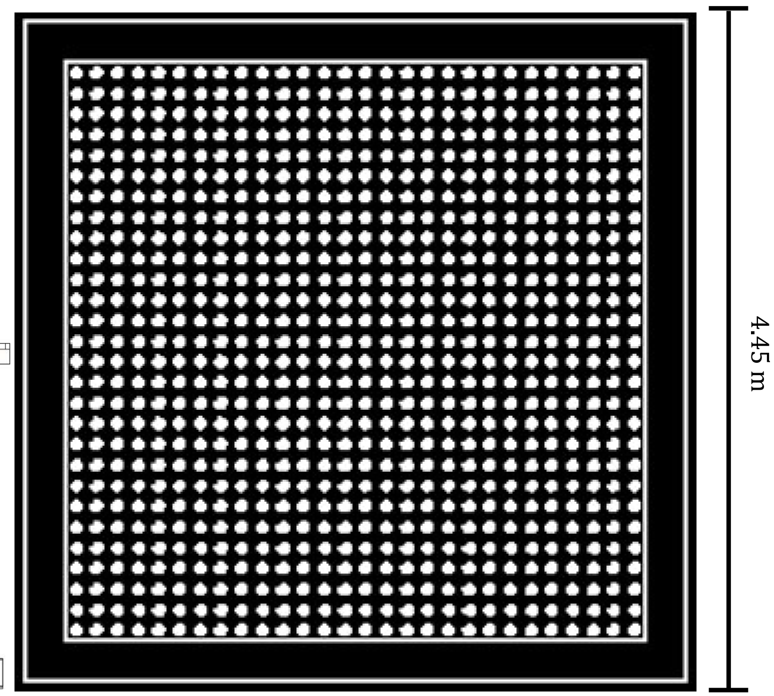
# HALO & HALO-1kT

- HALO lead based supernova detector.
  - 79 tonne lead volume with 128 $^3$He proportional counters (~1-2 m).
  - Observable signal from neutrino interactions in lead is out-going neutrons capturing on $^3$He.
- HALO-1kt: HALO's "bigger brother".
  - For several years has received R&D funding from NSERC.
  - Intent is to be located at Gran Sasso National Laboratory (Italy) and utilize the lead from the decommissioned experiment OPERA.
- HALO-1kT's geometry has been optimized to increase neutron capture efficiency.
  - Improvements have been made to shielding and sensitivity.
- Studies are underway for SN flux reconstruction, triangulation, proportional counter development, etc.

$n$ efficiency ~ 28%




$n$ efficiency ~ 53%




HALO and HALO-1kT side by side comparison. The model of HALO-1kT is a Geant4 model, rather than a schematic diagram.

# Event generation in HALO-1kT

- Event generation is handled by the SNOwGLoBES event calculator.
    - Folds neutrino fluxes with detector cross sections.
- Lead cross sections have not been measured, numerous calculations done from theoretical models.
    - i.e. isotopes of lead A = 204, 206 and 208, 1n/2n, neutrinos flavours (see top right).
    - Measurements will be preformed by the future miniHALO experiment at the SNS.
- Kolbe & Langanke provides interaction cross sections for various SN models (bottom right).
    - Fluxes modeled by Fermi-Dirac distributions with pinching parameter $\alpha$ and average neutrino temperature $\langle T \rangle$.
- Output from SNOwGLoBES provides temporal information of out-going neutrons.

CC

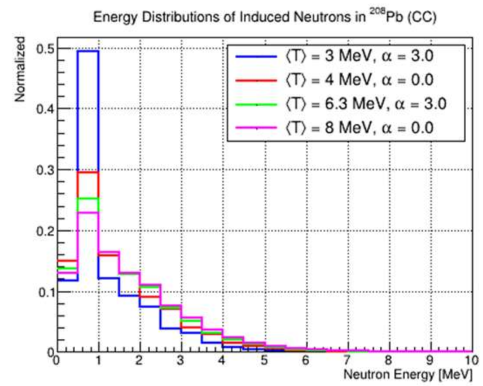
$$\nu_e + {}^{A}\mathrm{Pb} \rightarrow {}^{A}\mathrm{Bi}^{*} + e^{-}$$
$${}^{A}\mathrm{Bi}^{*} \rightarrow {}^{(A\text{-}1),(A\text{-}2)}\mathrm{Bi} + (1,2)n + \gamma$$

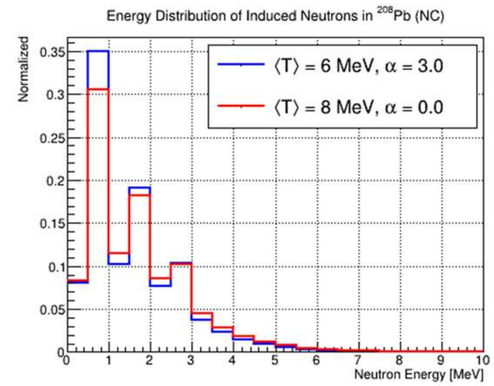
NC

$$\nu_x + {}^{A}\mathrm{Pb} \rightarrow {}^{A}\mathrm{Pb}^{*} + \nu_x$$
$${}^{A}\mathrm{Pb}^{*} \rightarrow {}^{(A\text{-}1),(A\text{-}2)}\mathrm{Pb} + (1,2)n + \gamma$$

| | Lead isotopes | | | Cross sec. | | CC/NC | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 204 | 206 | 208 | 1n, 2n | total | $\nu_e$ | $\overline{\nu}_e$ | $\nu$ | $\overline{\nu}$ |
| Kolbe | ✗ | ✗ | ✓ | ✗ | ✓ | ✓ | ✗ | ✓ | ✗ |
| Engel | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| Lazauskas | ✗ | ✗ | ✓ | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ |
| Almosly | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |

E. Kolbe, K. Langanke, Phys. Rev. C63 (2001).
J. Engel, G.C. McLaughlin, C. Volpe, Phys. Rev. D67 (2003).
R. Lazauskas, C. Volpe, Nucl. Phys. A792 (2007).
W. Almosly et al., Phys. Rev. C94 (2016) no.4 and Phys. Rev. C99 (2019) no.5.



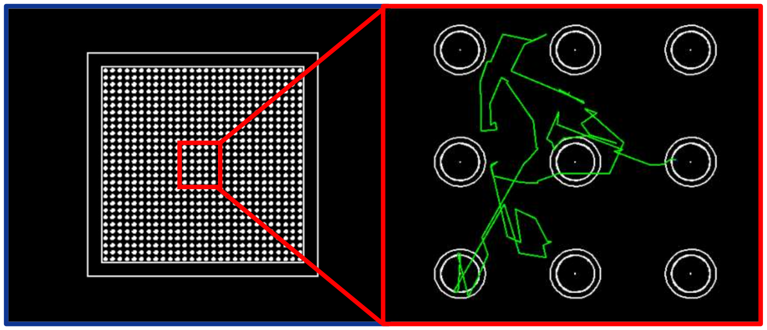



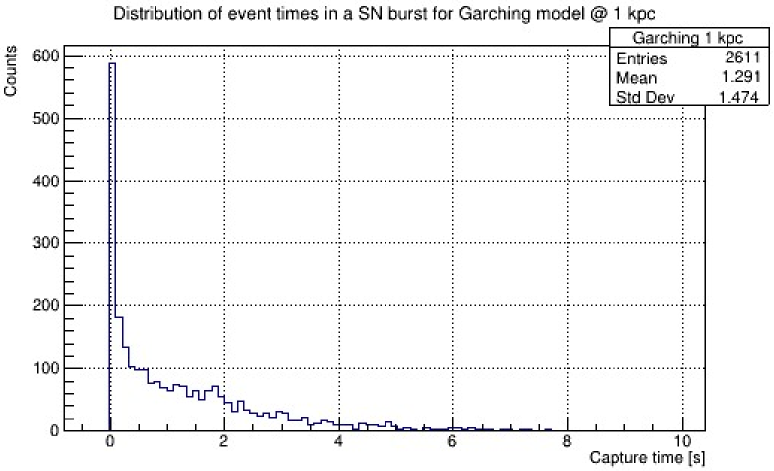
# Event simulation in HALO-1kT

- HALO-1kT makes use of a full-detail Geant4 Monte Carlo.
  - Output from SNOwGLoBES only provides temporal and multiplicity information of out-going neutrons.
  - Neutron energy sampled from Kolbe and Langanke (assume higher energy distribution for both CC and NC interactions).
  - Neutrons are uniformly created in lead volume (2n events share same generated position).
  - Momentum vectors of out-going neutrons assumed uniform, no correlation between the 2 neutrons in a 2n reaction.
- Full event is simulated up until the neutron captures on $^3$He via

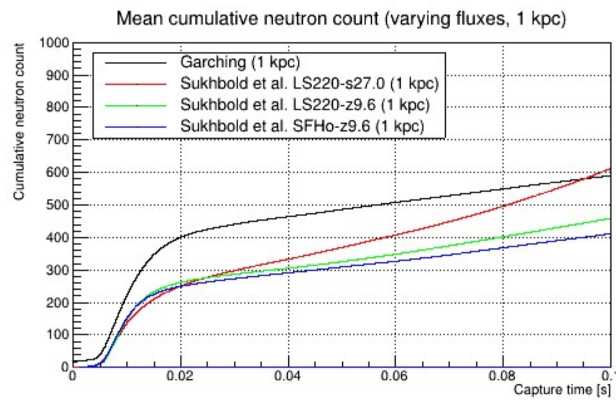
$$n + {}^3\text{He} \rightarrow t + p + 764\ \text{keV}$$

- For extraction of $t_0$, only care about the time of capture ($t_c$) and the indices of the event.
- Post simulation, a 1 Hz Possion background is added into the data.
- Capture time on the order of hundreds of $\mu s$.
  - Unbinned fitting technique required to extract $t_0$.
  - Using the first event not good enough (to much variability).





# Extracting $t_0$ using an unbinned maximum likelihood technique



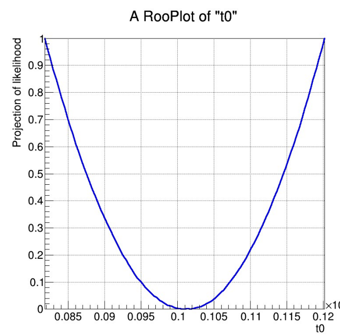

- For triangulation, HALO-1kT will need to extract $t_0$ with adequate precision.
  - i.e. Avoid binning data, problematic for SN at large distances from earth (not enough data).
- Assume that the data derives from a Poisson p.d.f defined by:

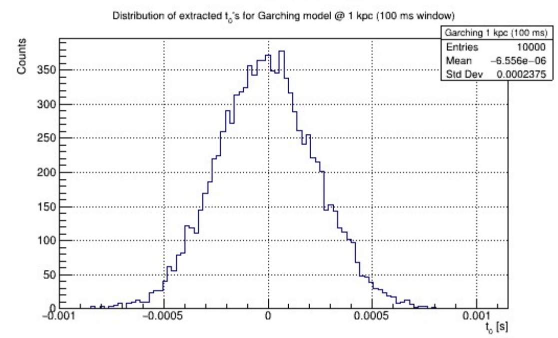
$$P[n(t_i);\bar{n}(t_i-t_0)] = \frac{\bar{n}(t_i-t_0)^{n(t_i-t_0)}\cdot e^{-\bar{n}(t_i-t_0)}}{n(t_i)!}$$

- The negative ln likelihood (NLL) is therefore:

$$\ell(t_0) = 2\cdot\sum_{i=1}^{N}\eta\cdot\bar{n}(t_i-t_0) + n(t_i)\cdot\ln(\eta\cdot\bar{n}(t_i-t_0))$$

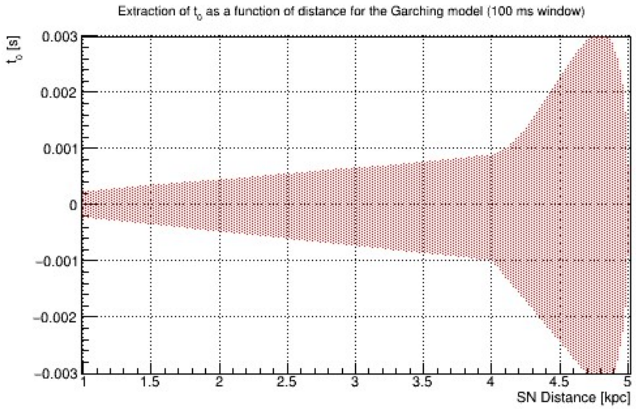
- Here, $n(t)$ is the vector of data with $N$ events (where $t_i$ is the time stamp of the i-th event), $\eta$ is the normalization condition and $\bar{n}(t)$ is the mean cumulative neutron count.
  - The determination of the mean cumulative count is depicted on the top right (exact technique is left in the backup slides).
- $t_0$ can be obtained from a minimization of $\ell(t_0)$ using MINOS/Minuit2.
  - An example of this can be found on the bottom left plot (where the errors on the extracted $t_0$ come from the points at $\ell(t_0)\pm 1$.
- The precision and resolution of the extracted $t_0$ can be quantified by repeating the NLL fit for $10^4$ SN bursts (see bottom right).
  - Fitting data to itself does not account for systematic uncertainties (no knowledge of 'model of best fit'). To do so, mix and match various models to quantify offset (see backup slides).

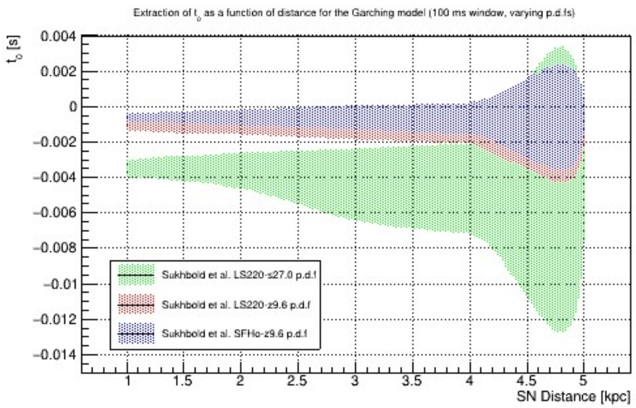


# Extraction of $t_0$ as a function of distance

- HALO-1kT expects excellent precision when extracting $t_0$ even out to ~4 kpc.
    - The above plot on the right is the Garching model (fitted to itself), with a 100 ms time window.
    - Shaded region represents the $1\sigma$ region obtained from integrating the extracted $t_0$ distribution.
    - On-going studies suggest that a smaller time window, 30 ms, would further improve the precision and resolution of the extracted $t_0$.
    - Although not covered in this talk (back up slides), fitting the Garching model to different p.d.fs does introduce systemic offsets (bottom right).
        - These can be reduced by optimization of the time window.
- The results on the right are preliminary and conservative in nature.



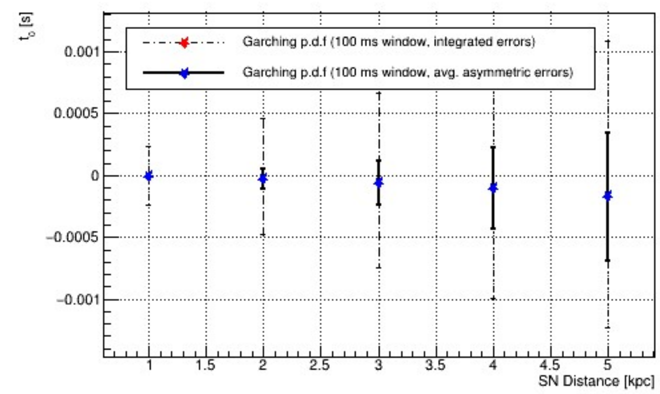



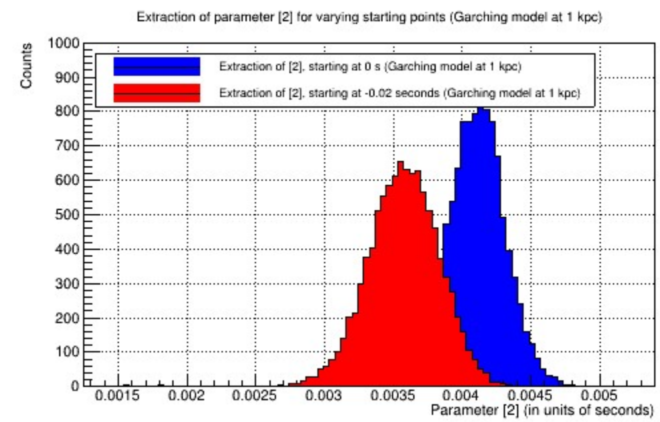
# Outlook

- HALO-1kT is close to quantifying its ability to contribute to the SNEWS 2.0 triangulation program.
- Once fully explored the intent is to extend this approach to HALO and SNO+.
    - For HALO, minimal changes need to be made since experimental configuration is largely the same.
- There are some ‘issues’ with our technique we investigating, mainly:
    - The mean of the asymmetric errors on $t_0$ do not accurately reflect the standard deviation of the $t_0$ distribution.
- We have begun looking into other techniques for extracting $t_0$. One such case is a linear fit (bottom right) defined as:

$$f(t) = [0] + [1] * (t - [2]) * (t > [2])$$

- Where parameter [2] gives us a relative location for each unique model.



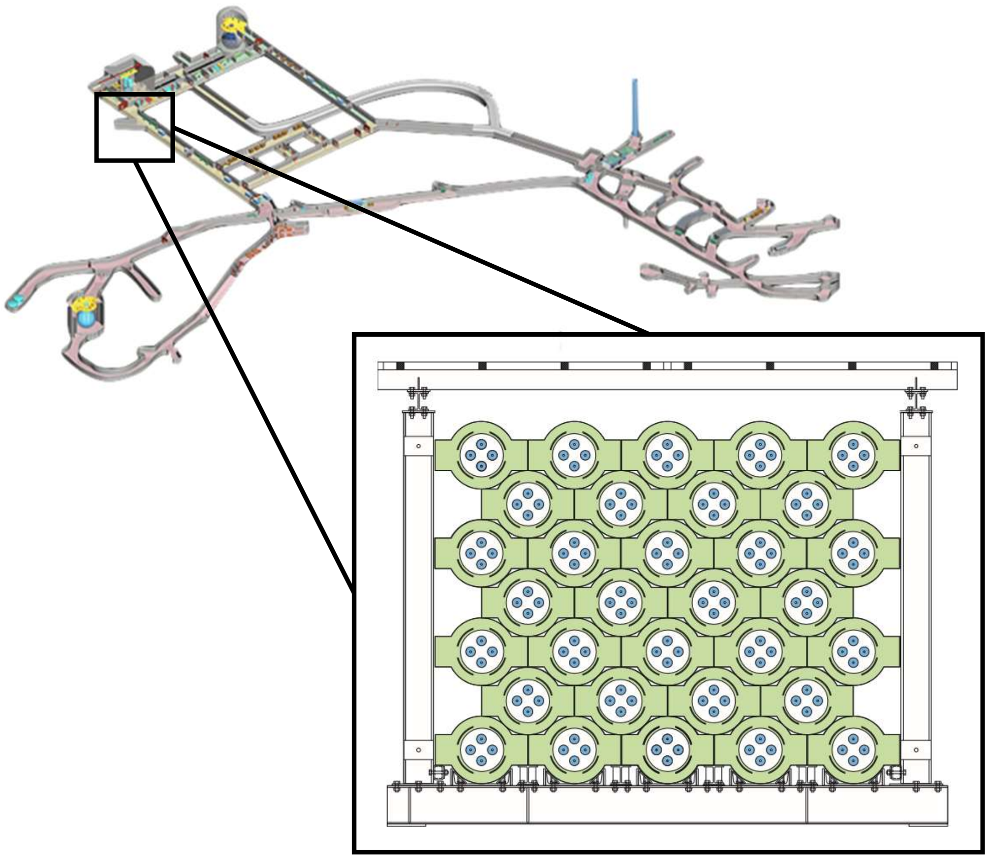
# Thank you for listening! Questions?

LaurentianUniversity
UniversitéLaurentienne

EMITTE LUCEM ET VERITATEM

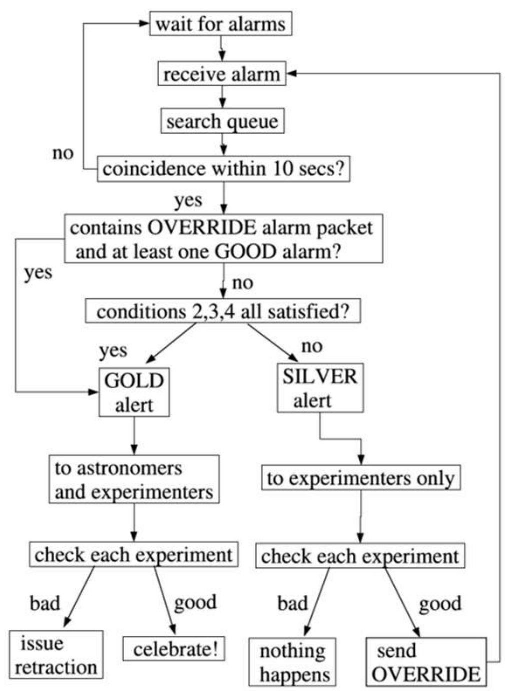
# The Helium and Lead Observatory (HALO)

- Located at SNOLAB in Creighton Mine (Sudbury, ON).
  - Operational since May 2012 (joined Supernova Early Warning System (SNEWS) in Oct. 2015).
- 79 tonne lead volume with 128 $^{3}$He proportional counters (~1-2 m).
  - Observable signal from neutrino interactions in lead is out-going neutrons capturing on $^{3}$He.
- 'Detector of opportunity':
  - Lead from cosmic ray monitoring experiment at Deep River.
  - Prop. counters from SNO (ultra-pure nickel 'NCDs', measured $n$ from NC interaction $\nu_x(d,np)\nu_x$).
- Dedicated supernova neutrino detector.
  - Sole SN detector that operates with lead volume (primarily $\nu_e$ sensitive, $\overline{\nu_e}$ CC heavily suppressed).



# SuperNova Early Warning System (SNEWS)

- SNEWS Formed in the late 90’s, operating since 2005.
- Purpose is to coordinate response to $\nu$ signal in multiple $\nu$ detectors.
  - Alerts, triangulation, etc.
- Intent is to alert astronomical community of impending supernova.
  - False coincidences happen with frequency “not in my lifetime”.
- Three P’s of SNEWS:
  - Prompt
  - Pointing
  - Positive
- Successful SNEWS 2.0 Workshop at Laurentian University in June.




Alarm scheme for SNEWS (server is located at Brookhaven National Laboratory).

Each experiment is tasked with issuing alerts they deem probable supernovae.

For HALO, events can be classified as 1) SN candidate 2) Coincidence 3) Spallation 4) Other 5) etc.

# Normalization

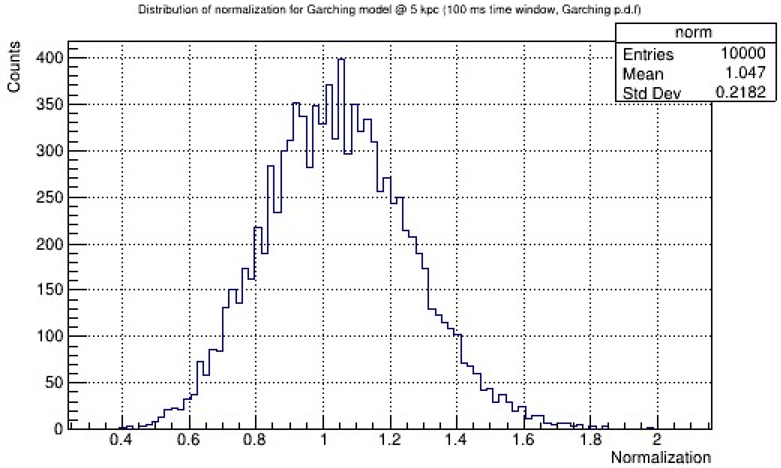
- A normalization term is introduced in the NLL

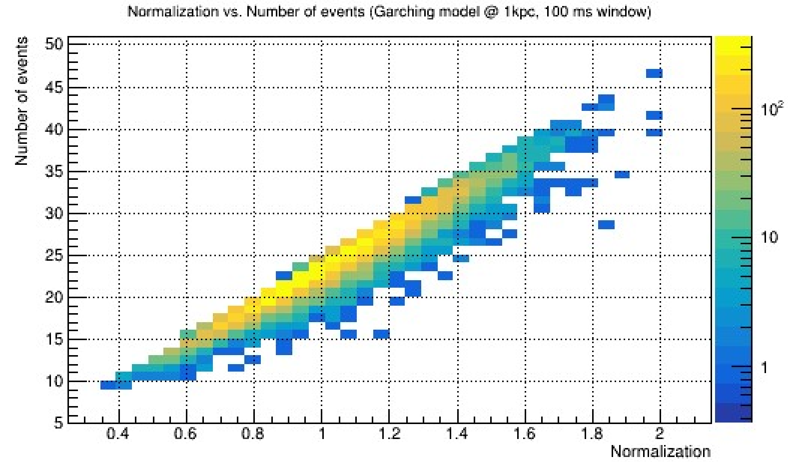
$$\ell(t_0) = \sum_{i=1}^{N} \eta \cdot \bar{n}(t_i - t_0) + n(t_i) \cdot \ln(\eta \cdot \bar{n}(t_i - t_0))$$

- Where $\eta$ is defined as

$$\eta = \frac{n(t_N)}{\bar{n}(t_N)}$$

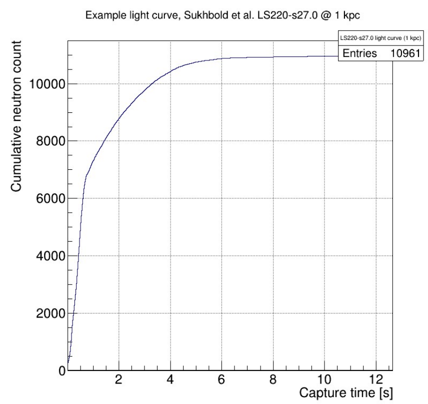
- This term is intended to scale the mean cumulative neutron counts ($\bar{n}(t)$) to the same fixed end point as the simulated/observed data ($t_N$).
- On the top right is the normalization for the Garching model at 5 kpc.
- On the bottom right is the same model/distance with the normalization as a function of number of events.

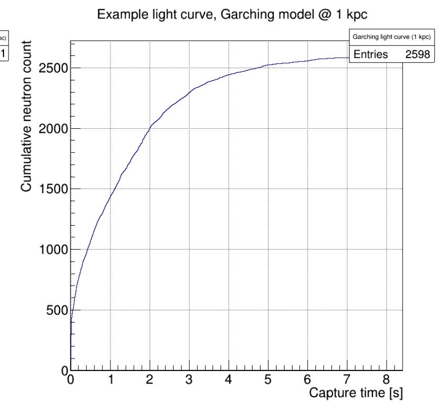


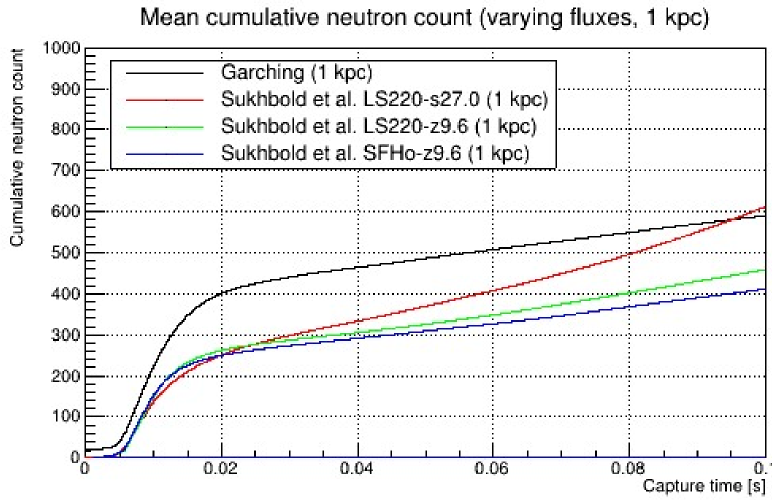



# Creating the mean cumulative neutron count

- Output from SNOwGLoBES is simulated through a model of HALO-1kT in Geant4.
  - Result is a $1 \times N_b$ vector, where $N_b$ is the number of events in the burst.
  - $N_b$ varies between simulated bursts due to Poisson fluctuations carried out on SNOwGLoBES output.
- $10^4$ bursts simulated in the detector, providing adequate statistics.
- All bursts 'appended' into a $1 \times [N_1 + N_2 + \ldots N_t]$ vector.
  - Where $N_t$ is the number of bursts simulated.
- Vector is sorted and normalized to the mean number of events expected for a given model and distance.

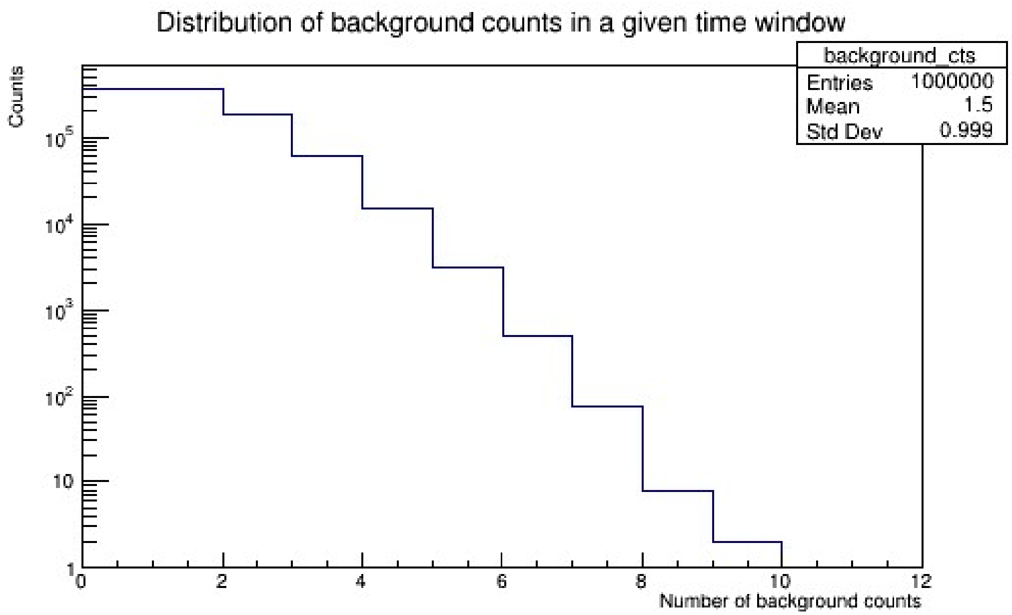


# Background model

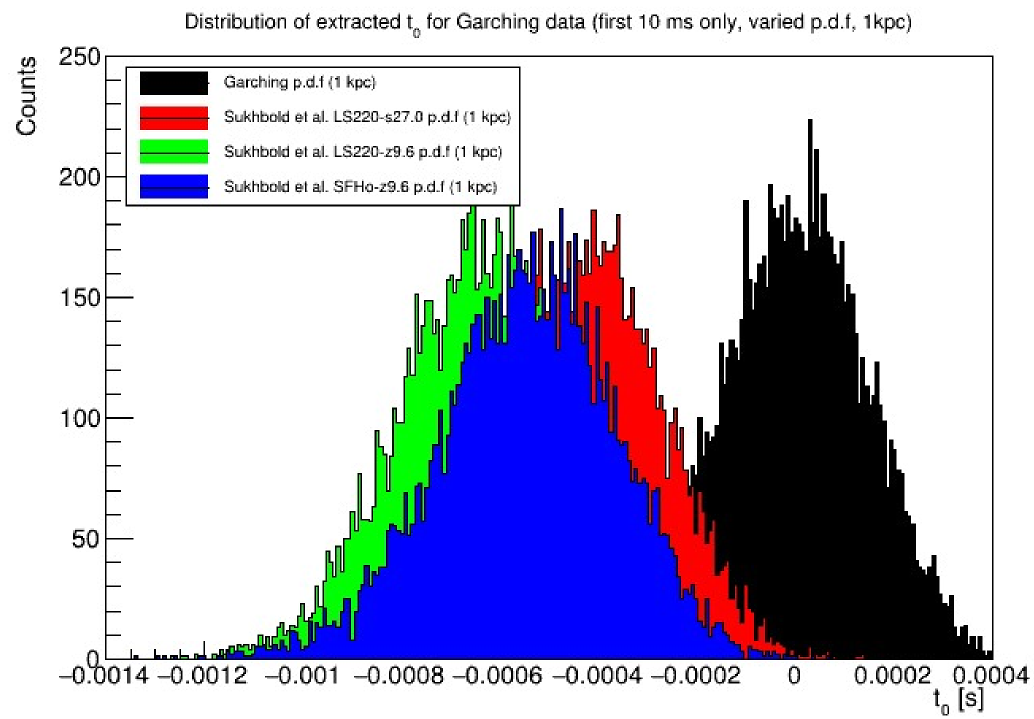
- HALO-1kT is under active R&D; as of now, only upper limits exist on background rate in the ROI.
  - ROI = [191, 764] keV (neutron produced triton-proton pair).
- Current upper limit (summed across all channels) on background rate is placed at 1 Hz.
- Treat this background as a Poisson PDF with mean ($\lambda$) = 1.0 (Hz).
- For each second in a simulated SN burst, sample the PDF.
  - For each event returned (or not), sample a uniform random time in that window.




Note: Above is a multiplicity distribution produced by sampling the Poisson PDF $10^6$ times.

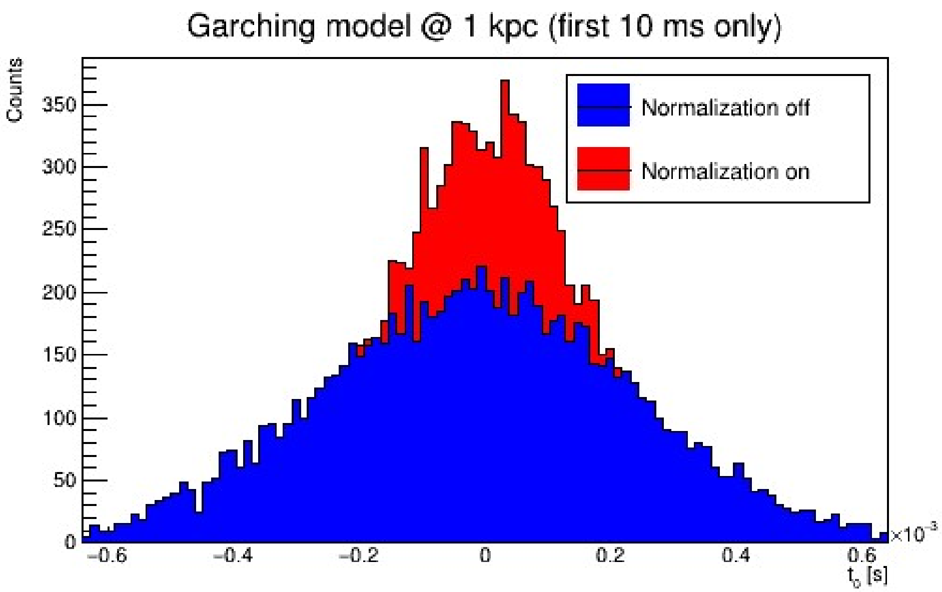
# Model mixing

- When extracting $t_0$, there will be no knowledge of what p.d.f it belongs to (if at all, only models).
- As a result, to quantify systematic uncertainties, we fit different models and p.d.f combinations.
    - On the right (top), the Garching data at 1 kpc was fit to varying p.d.fs.
    - The result is a systematic offset of 400-700 $\mu s$ (depending on the model).
- This can be extrapolated out to further distances (see bottom right).



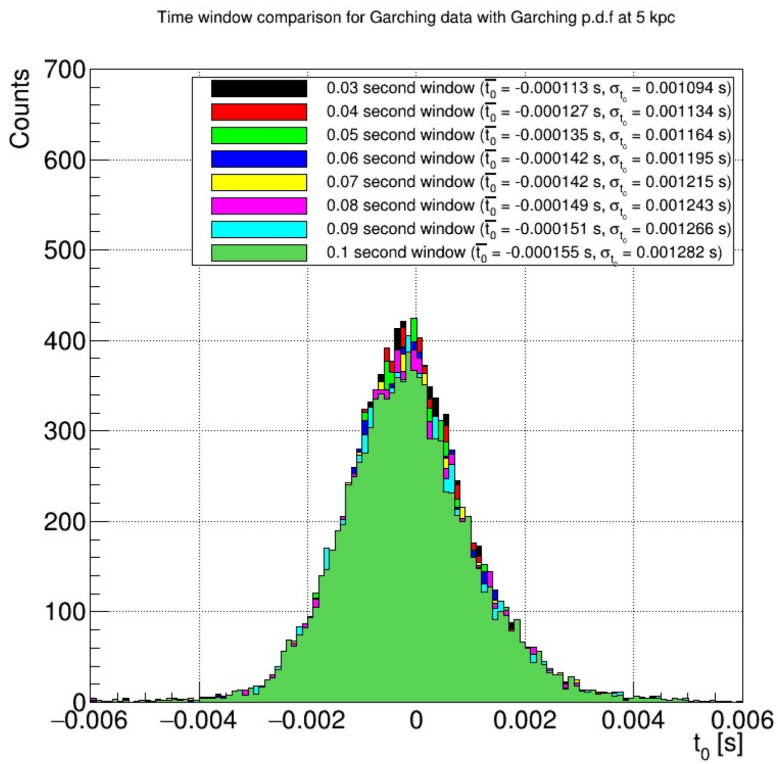
# Impact of normalization

- During an investigation into the discrepancy of the likelihood errors, we investigated if the normalization was the cause.
- With the normalization turned off, the resolution on the extraction of $t_0$ is decreased (see right).
  - Although positioning of the mean is the same (within error).



# Varying the time window for Garching data/p.d.f

- Depicted on the right is the extracted $t_0$ from the Garching model and p.d.f with varying time windows.
- I did test down to 0.01 and 0.02 seconds but the performance was poor due to a general lack of events populating the burst.
    - Time window usually ended before the start of the peak following $t_0$.
- If we look at the distributions on the right it becomes clear that for the Garching model, the best performance comes with a window selection of 30 milliseconds.
    - The error on the means is too low to account for the amount of shift observed between the 5 distributions.



# Varying p.d.f distance

- During our studies, we begun to wonder if varying the p.d.f distance had any impact on the likelihood.
- The general shape sees negligible changes out to > 5 kpc.
  - Background rate is low enough, 1 Hz, that there is little impact.
- Depicted on the lower right is the Garching data at 5 kpc with the Sukhbold et al. LS220-s27.0 p.d.f at varying distances.
  - You will observe little to no effects on resolution or position of $t_0$ distribution when p.d.f distance is varied.
- The results on the right make clear that the p.d.f distance has no impact on the extraction of $t_0$, the only parameter of interest.