CREDITS: ESA/Hubble & NASA

Lead-based Supernova Detectors

C.J. Virtue for the HALO Collaboration

SNOLAB

Outline

- Basics – what?
- Rationale / Drawbacks – why?
- Lead-based Supernova detection
  - Cross sections / Flavour sensitivity
- HALO at SNOLAB
  - Neutron Detection
  - Backgrounds
  - SNEWS
  - Performance
- Future
  - HALO
  - HALO-1kT?

Basics

- A lead-based supernova detector is a volume of target lead, some neutron moderating material, instrumented with neutron detectors, and shielded from external background neutrons
- Supernova neutrinos can excite, through Charged-Current (CC) and Neutral-Current (NC) interactions, states in Pb above the 1-neutron and 2-neutron separation energies
- These neutrons have MeV energies and are thermalized and detected with some efficiency
- A near-enough supernova would produce a burst of detected neutrons and result in a very low-latency alarm to SNEWS
- Flavour sensitivity implies contributions to global SN data analyses (A. Gallo Rosso – yesterday)

Rationale

In Summary

- Complementarity of neutrino flavour sensitivity vis-à-vis water Čerenkov and liquid scintillator detectors
- Robust technology, low-cost, low-maintenance, high-livetime
- Simple → low latency signal to SNEWS

Merits for a dedicated SN detector!

Drawbacks

- Cross section uncertainties
- No CC / NC separation
- No directional information
- T_0 precision limited by statistics
- Lacking technical challenge to attract and retain talent new projects or for long-term operation?
- Laurentian Insolvency has forced / accelerated a change from a Laurentian-centric operation of HALO to a SNOLAB-centric one

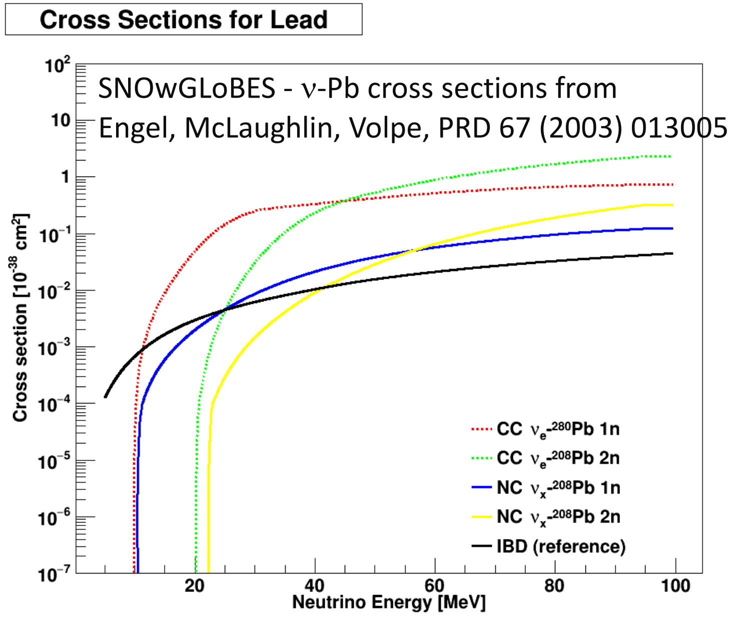
Cross sections

- The following reactions can occur for neutrinos of supernova energies

$$
\begin{aligned}
\mathrm{CC:}\quad & \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 9.8\,\mathrm{MeV} \\
& \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 17.9\,\mathrm{MeV} \\
\mathrm{NC:}\quad & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV} \\
& \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}
\end{aligned}
$$

- electrons carry energy information and could be used to tag CC reactions, however
  - requires lead in solution – was explored and abandoned, or
  - requires fine-grained lead-scintillator – also abandoned
  - so no CC tagging or energy measurement
- neutrons detected through capture on ^{3}He after thermalization (200 μs)
  - no energy measurement, though some sensitivity through 2n / 1n ratio
  - no direction measurement
  - only counting as a function of time, single (1n) and double (2n) events

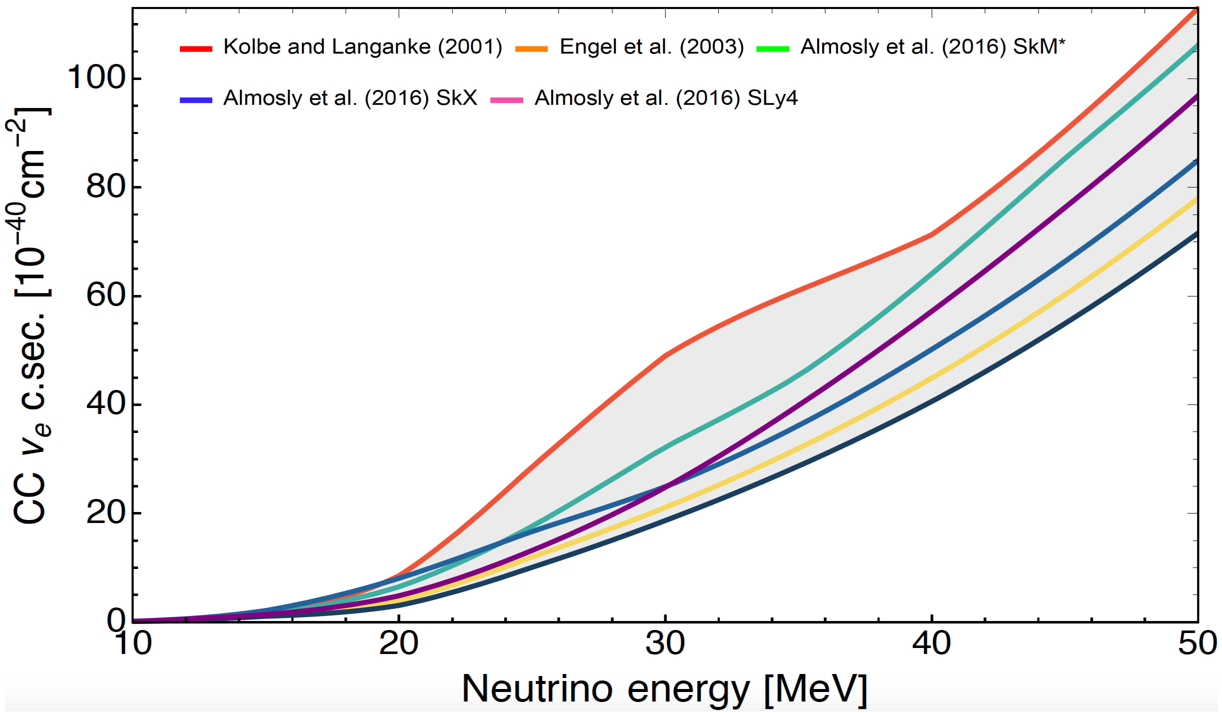
Note: no $\overline{\nu}_e$ CC
Pb has a very low n-capture cross section
(α,n) on Pb has threshold above U/Th α's



Available Cross Sections for Lead

	Lead isotopes			Cross sec.		CC/NC			
	204	206	208	1n, 2n	total	ν_e	$\bar{\nu}_e$	ν	$\bar{\nu}$
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.

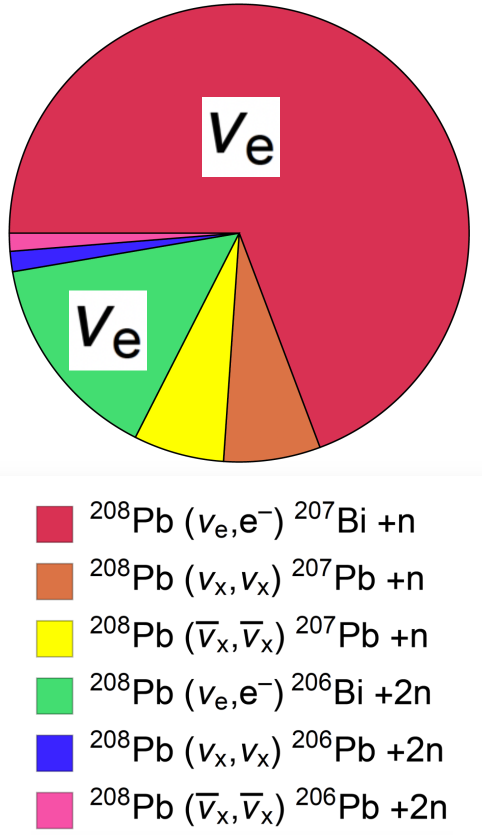


★ Only calculation that includes 1n, 2n separately; also conservative compared to others

See talk Y. Efremenko this afternoon

Flavour sensitivity

- the nuclear physics of lead strongly affects the interaction rates
  - the neutron excess in Pb Pauli blocks $\overline{\nu}_e$ CC reactions
  - the high Z further Coulomb suppresses $\overline{\nu}_e$ CC and enhances ν_e CC
- the response remains an unresolved mixture of ν_e CC and ν_x NC but is largely orthogonal to $\overline{\nu}_e$ CC (IBD) sensitivity of LS and WC detectors
- part of the merit of a lead-based supernova detector rests on its complementary flavour sensitivity wrt other SN detectors and the power it brings to joint analyses



A. Gallo Rosso

Neutrino-Induced Neutrons (NINs)

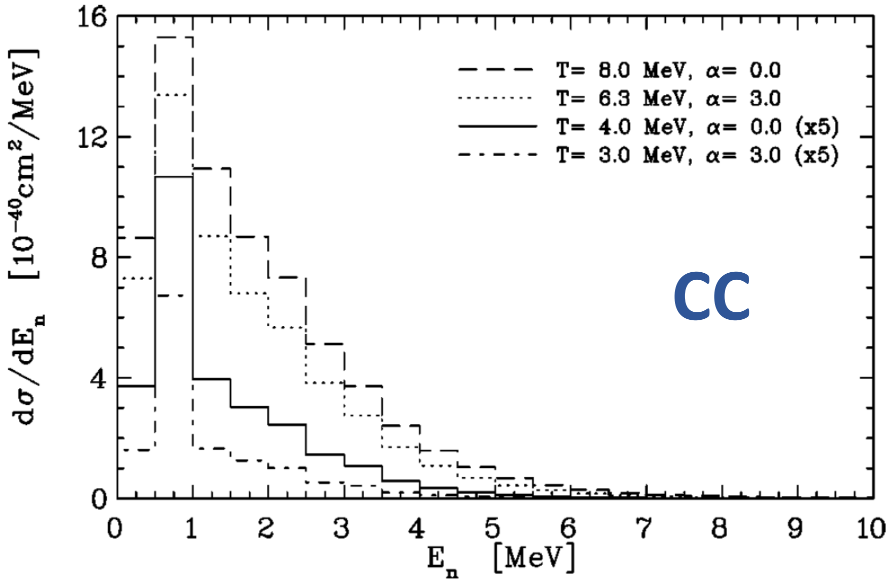


FIG. 6. Neutron energy spectrum produced by the charged-current (ν_e, e^-) reaction on ^{208}Pb. The calculation has been performed for different supernova neutrino spectra characterized by the parameters (T,α). Note that the cross sections for $(T,\alpha)=(4{,}0)$ and (3,3) neutrinos have been scaled by a factor of 5.

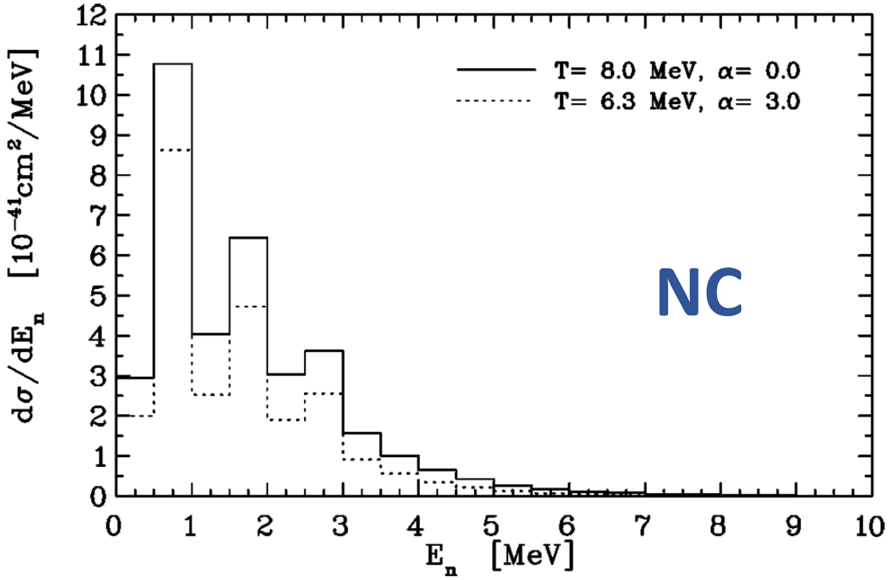


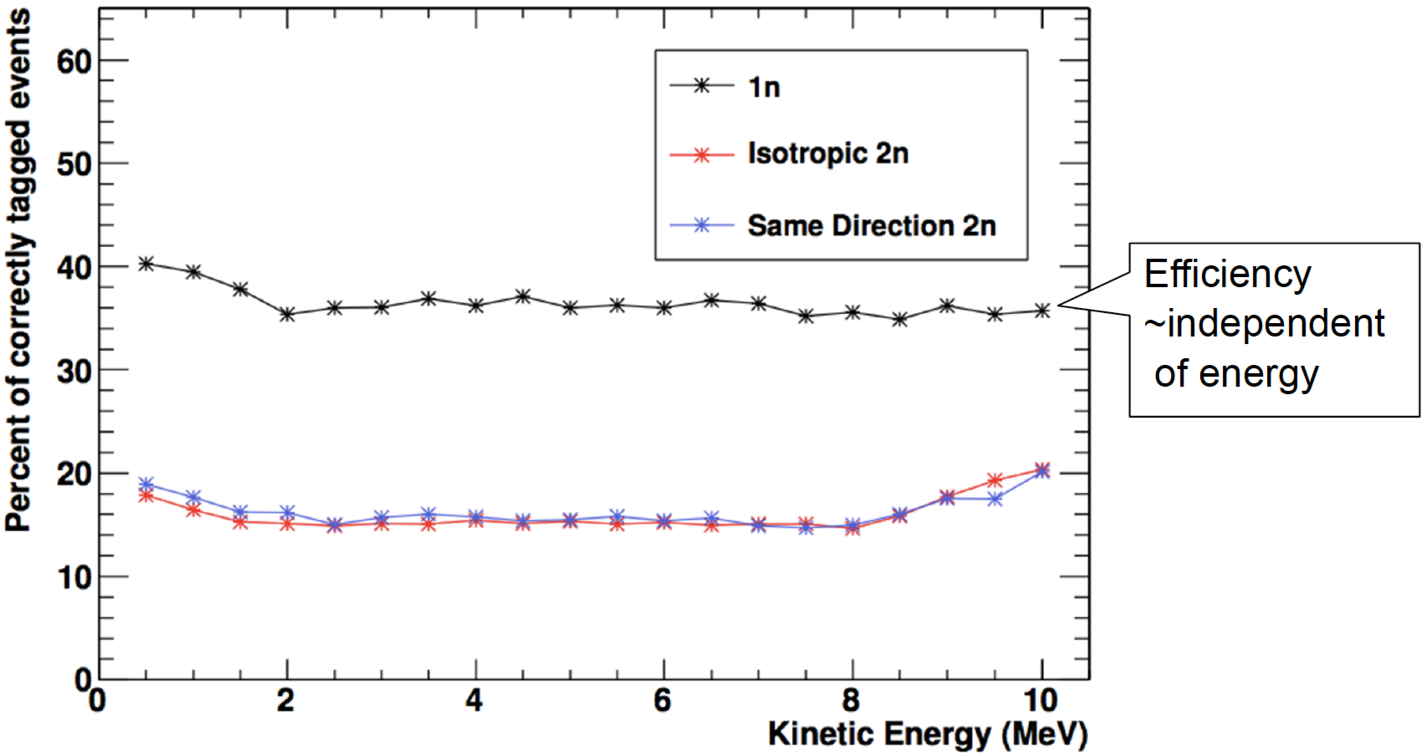
FIG. 7. Neutron energy spectrum produced by the neutral-current (ν,ν') reaction on ^{208}Pb. The calculation has been performed for different supernova neutrino spectra characterized by the parameters (T,α).

Kolbe and Langanke, PRC 63 (2001), 025802

Thermalization and capture time ~200μs

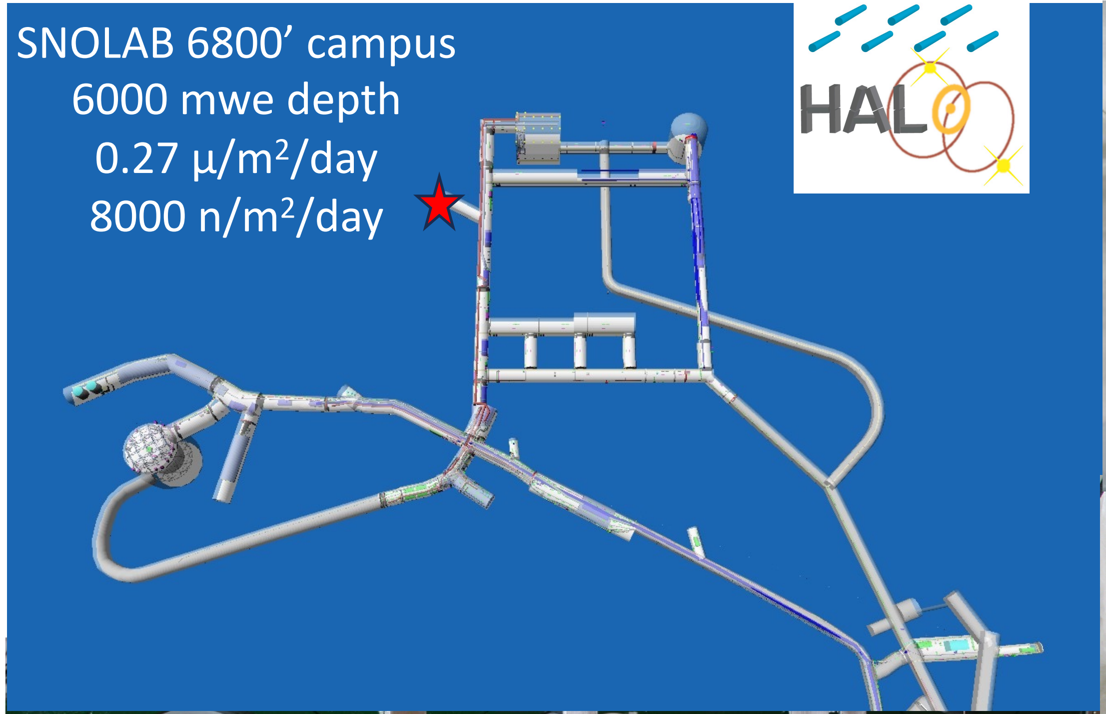
Sensitivity to NIN energy and angular distribution

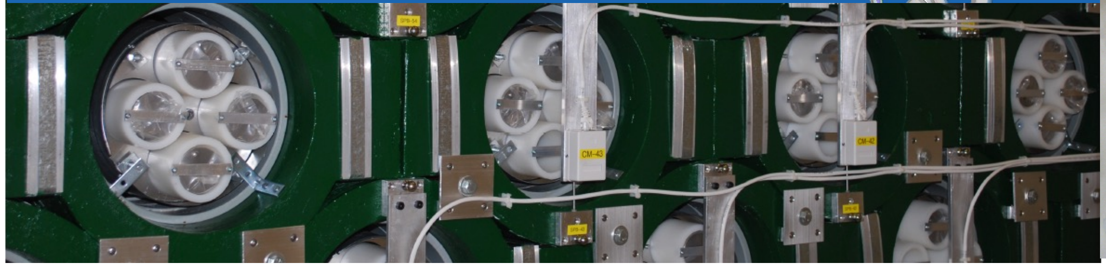
- Tested in Monte Carlo by scanning neutron energy with random position / direction
- For 2n did both isotropic and collinear
- No sensitivity found
- Monte Carlo samples the Kolbe / Langanke distributions nonetheless
- Plot done with earlier version with slightly higher neutron capture efficiency



HALO Geant4 simulation study
Leigh Schaefer, TUNL REU @Duke, summer 2011
(eff somewhat lower in current sim – but shape and relative effs the same)

HALO at SNOLAB

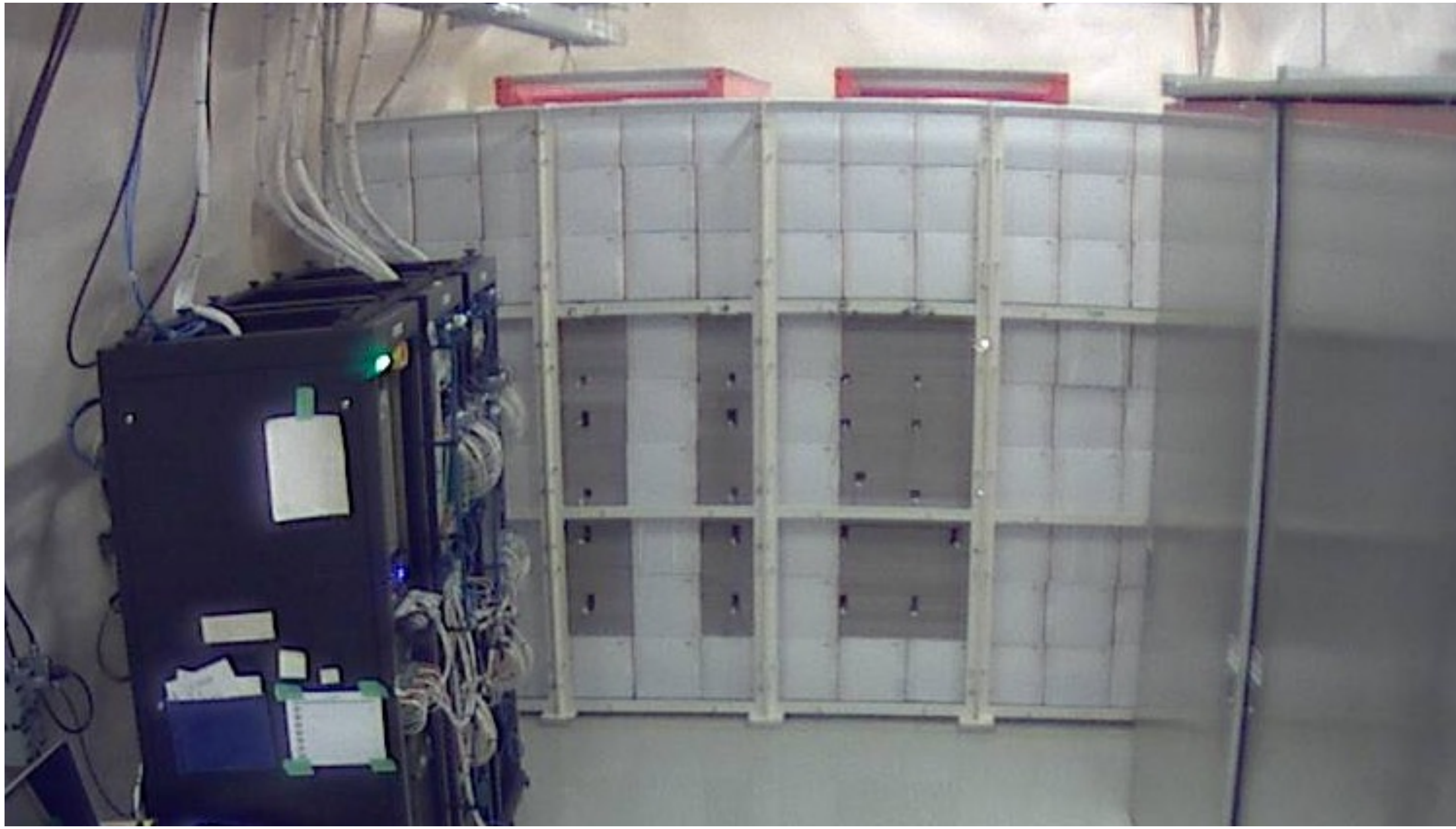




- “Helium And Lead Observatory”
- SNO’s ^{3}He counters
  - 128 excellent low background neutron detectors (368 m containing ~1465 litre.atm ^{3}He)
- 79 tonnes of Pb
  - 864 91kg blocks, non-optimum lead geometry
- 8mm HDPE moderator sleeves

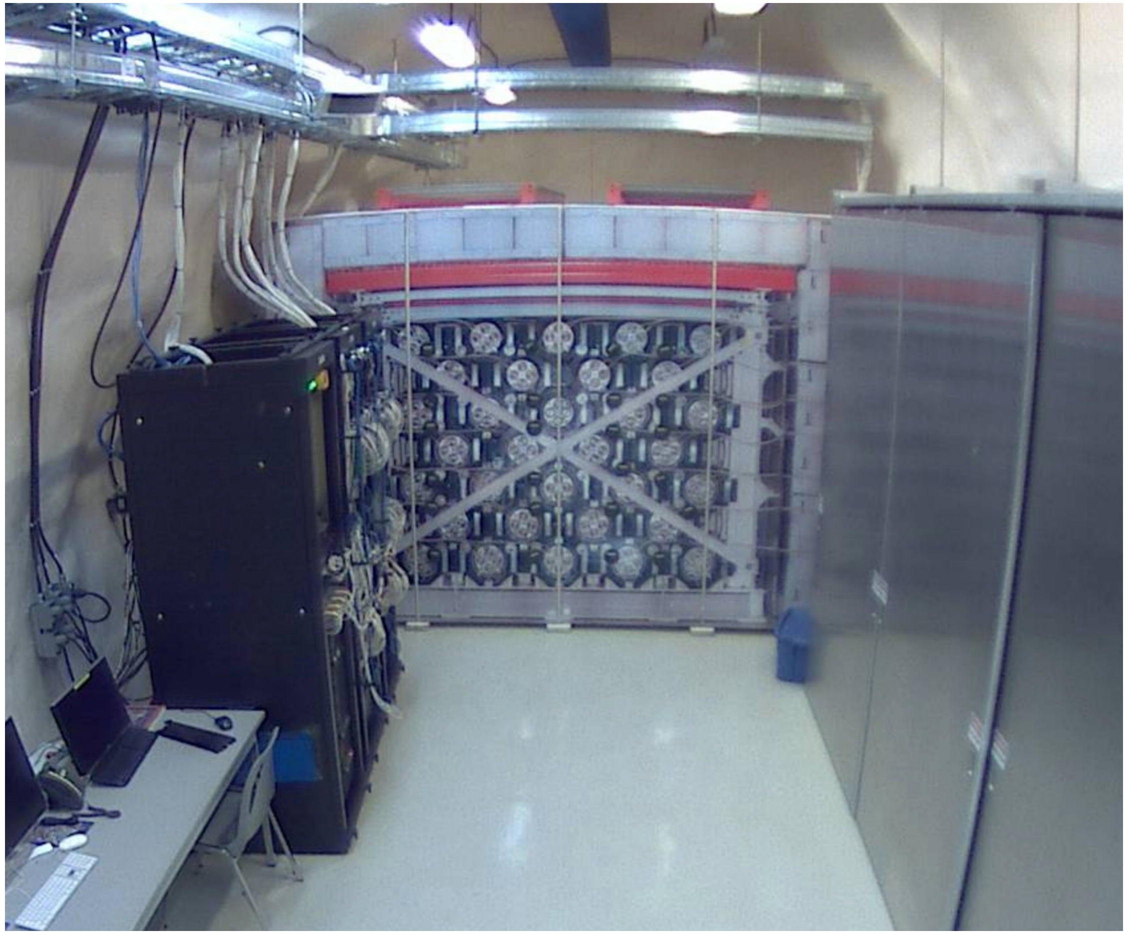
Shielding

- Modest requirements
- Stacked cubic foot "water boxes" on 5 sides
- 20 cm plastic lumber underneath
- Provision for 24 calibration tubes in front
- Adequate to reduce detected neutrons to 15 mHz (1 per minute)



Status today

- Full detector being read-out since May 8th 2012
- Entering 12th year of continuous high livetime operation
- Daily shift-taking since July 27th 2012.
- Burst trigger implemented and connected to SNEWS since October 8, 2015
- Full calibration done with and without front shielding wall April 2016
- simulated / calibrated / understood
- many redundant systems for reliability



Redundancy

- the basics
  - power
    - UPS with ~2 hours runtime; automated shutdown and restart around extended power failures
    - Recently SNOLAB has added a 3 MW diesel generator to supply entire lab
  - network
    - two switches – stacked with multiple uplinks and spanning tree to manage multiple single points of failure
  - GPS
    - two units – surface and underground
    - Oven-ized oscillator in underground one in case fiber to surface lost

Redundancy

128 ^{3}He neutron detectors
- paired → 64 channels

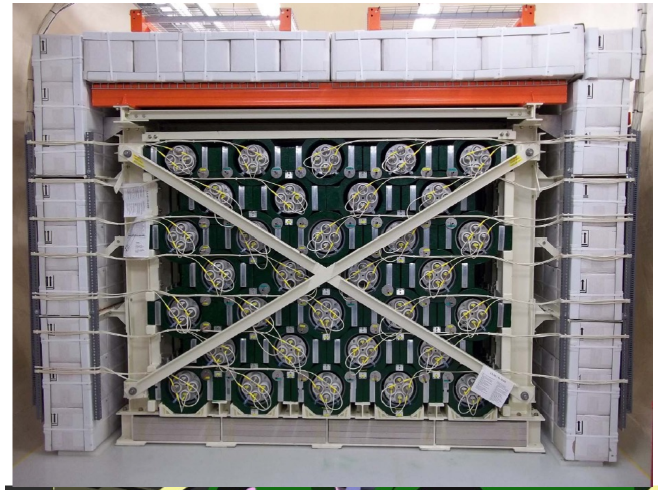
Required (one of):
- LV preamp power supply
- HV supply
- ADCs
- DAQ computer

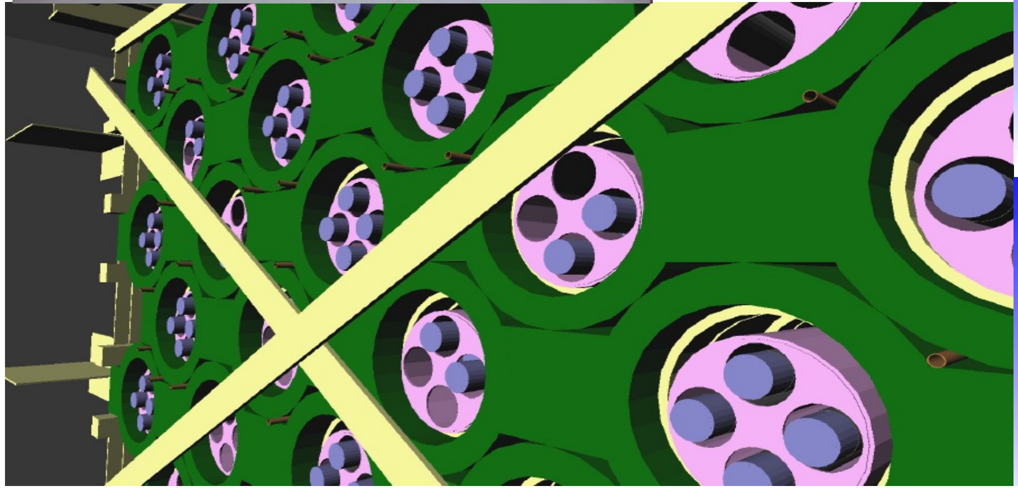
But multiple single points of failure, so:
- divide readout left / right
- double-up on components including DAQ computer

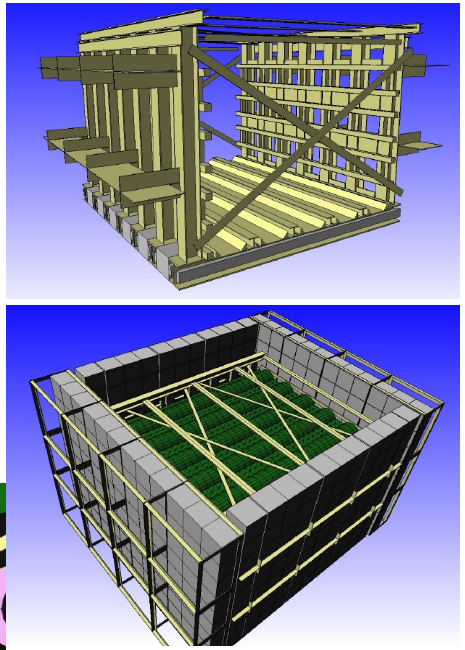
Most single point failures leave 50% of readout functioning

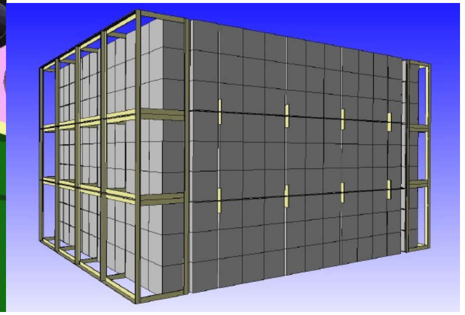
Simulation

- Initial design optimization done with simplified Geant4 geometry
- Fully detailed "as built" geometry added later
- Emphasis on simulating / optimizing neutron capture efficiency and detector calibration
- Later studied SN "light curves" and t_0 extraction for SNEWS



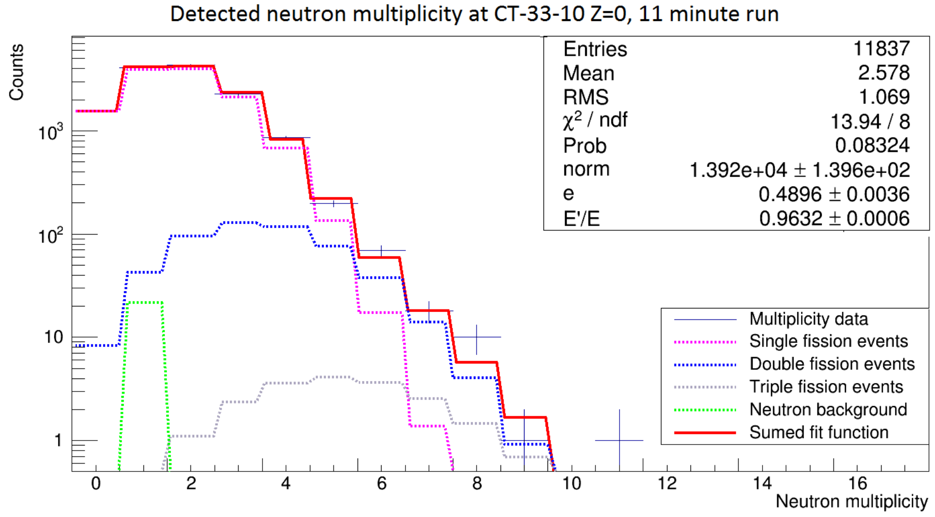


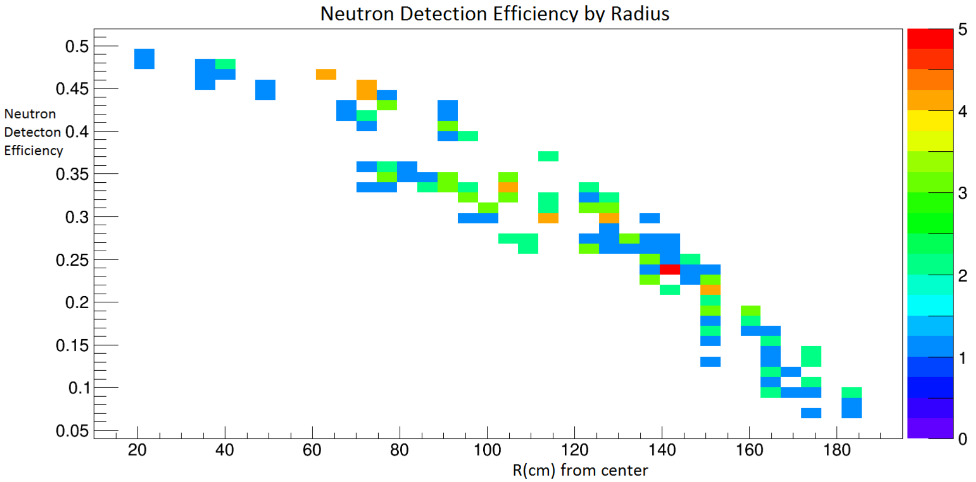




Calibration

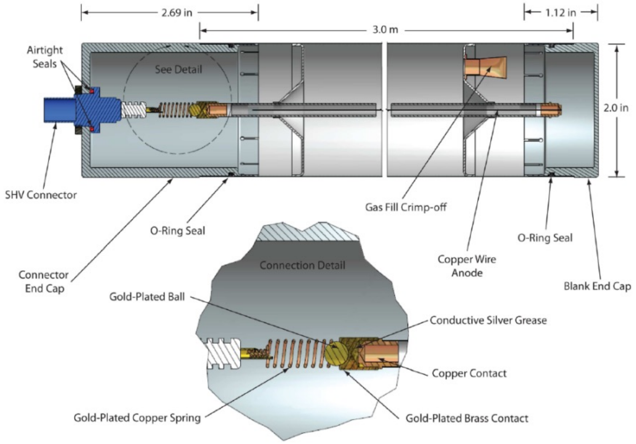
- used a low activity (~20 SF/s) ^{252}Cf source
- with very low backgrounds were able to measure the neutron multiplicity distribution which is a strong function of the neutron capture efficiency at 192 points
- extend time window to ensure that all neutrons from an integral number of fissions were counted
- fitting simultaneously gives efficiency at a point and the source strength
- rely on Monte Carlo simulation to extrapolate from 192 discrete calibration points to a volume-averaged efficiency for distributed supernova neutrino neutron production → 28% volume-averaged
- Caveat: ^{252}Cf neutron multiplicity distribution assumed.... Evaluating systematic associated with other isotopes present

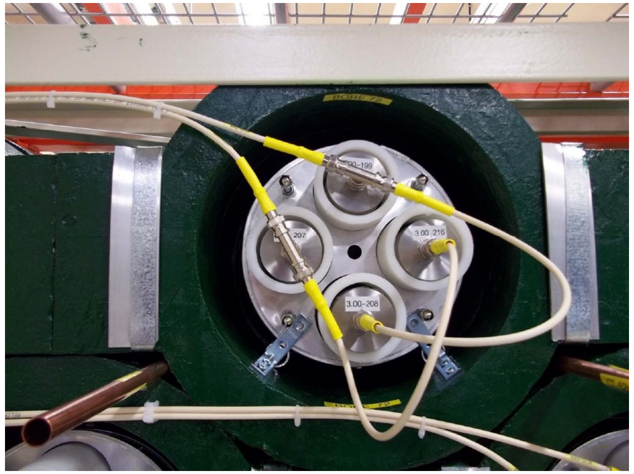




Neutron detection

- Re-using SNO's "NCD" ^{3}He proportional counters
- 5 cm diameter x 3 m and 2.5 m in length, ultra-pure CVD Ni tube (600 micron wall thickness)
- 2.5 atm (85% ^{3}He, 15% CF_4, by pressure)
- New endcaps and HV connection designed for HALO
- Four detectors with HDPE moderator tubes in each of 32 columns of lead rings
- 128 counters (368 m) paired for 64 channels of readout

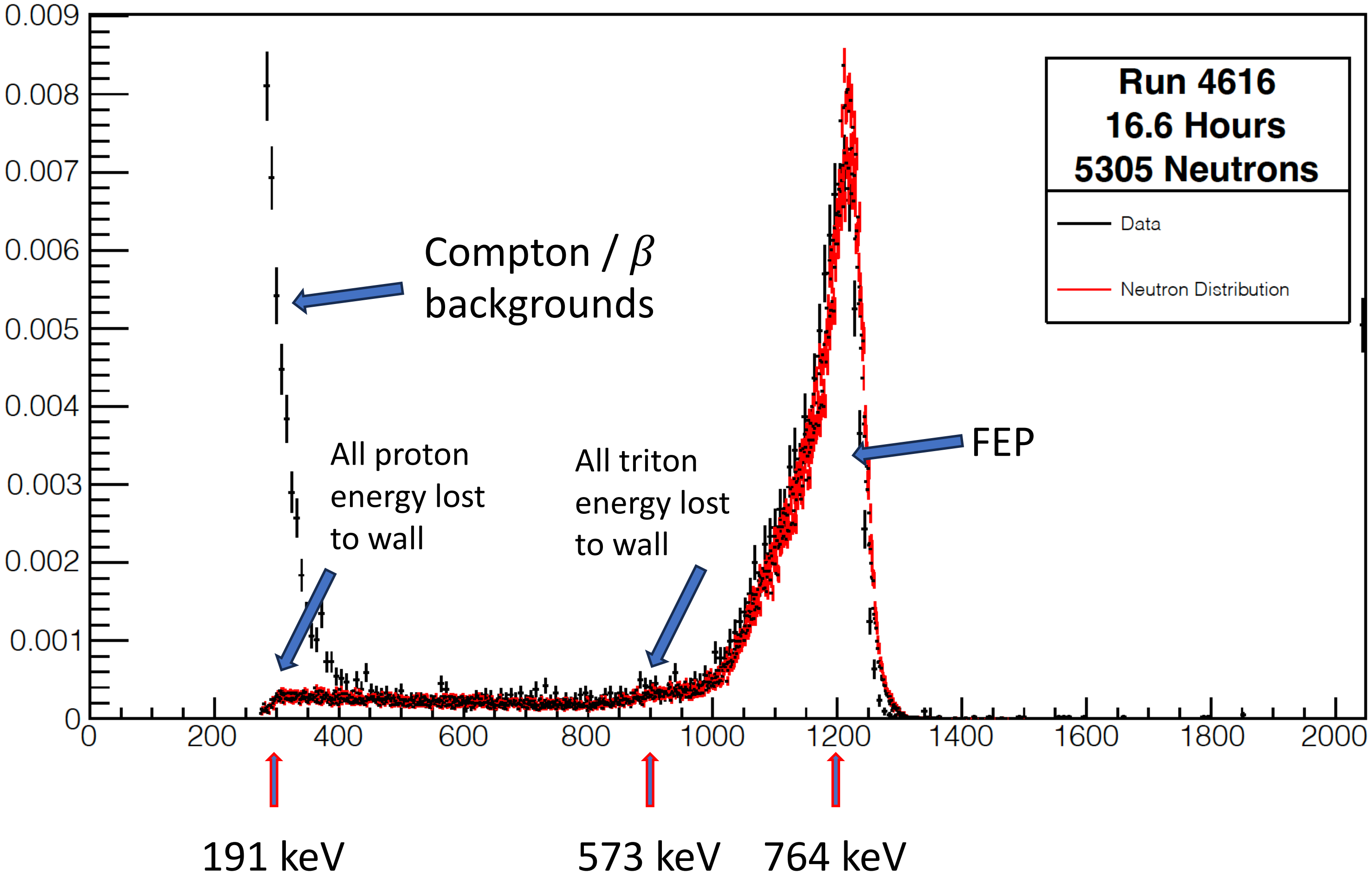




Neutron detection

n + ^{3}He → ^{3}H + p + 764 keV

- Energy divided
  - Proton – 573 keV
  - Triton – 191 keV
- FEP tuned to ADC channel 1200
- Reduced integration time wrt SNO
  - Degraded energy resolution at FEP
  - Less efficient charge collection for longer Compton / β tracks
- For SN trigger we define a "neutron" as > ADC channel 400, < 1350



Backgrounds

- Cosmic muons (< 2 / day) → spallation
- Spontaneous fission of built-in ^{238}U
  - Have seen 398 Spallation / SF bursts (> 3 "neutrons" in 2 s window) in last 444 days
- Environmental neutrons (α, n) in surrounding rock
  - 4000 thermal / m^2 / day
  - 4000 fast / m^2 / day
  - Responsible for bulk of 15 mHz of "neutrons"
- Proportional tube wall alphas
  - ~ 1 / m / day but only ~20% fall in neutron window
- Compton / β
  - Set channel thresholds around ~50 keV for flat rate across the 64 channels and total DAQ rate of 5 Hz

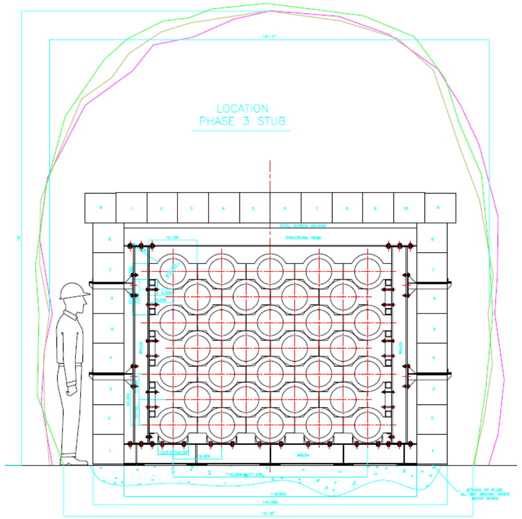
Supernova signal in HALO

CC: $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$

$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$

NC: $\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$



In 79 tonnes of lead for a SN @ 10kpc†,

- Assuming FD distribution with T=8 MeV for ν_μ's, ν_τ's.
- 68 neutrons through ν_e charged current channels
  - 30 single neutrons
  - 19 double neutrons (38 total)
- 20 neutrons through ν_x neutral current channels
  - 8 single neutrons
  - 6 double neutrons (12 total)

~ 88 neutrons liberated; ie. ~1.1 n/tonne of Pb

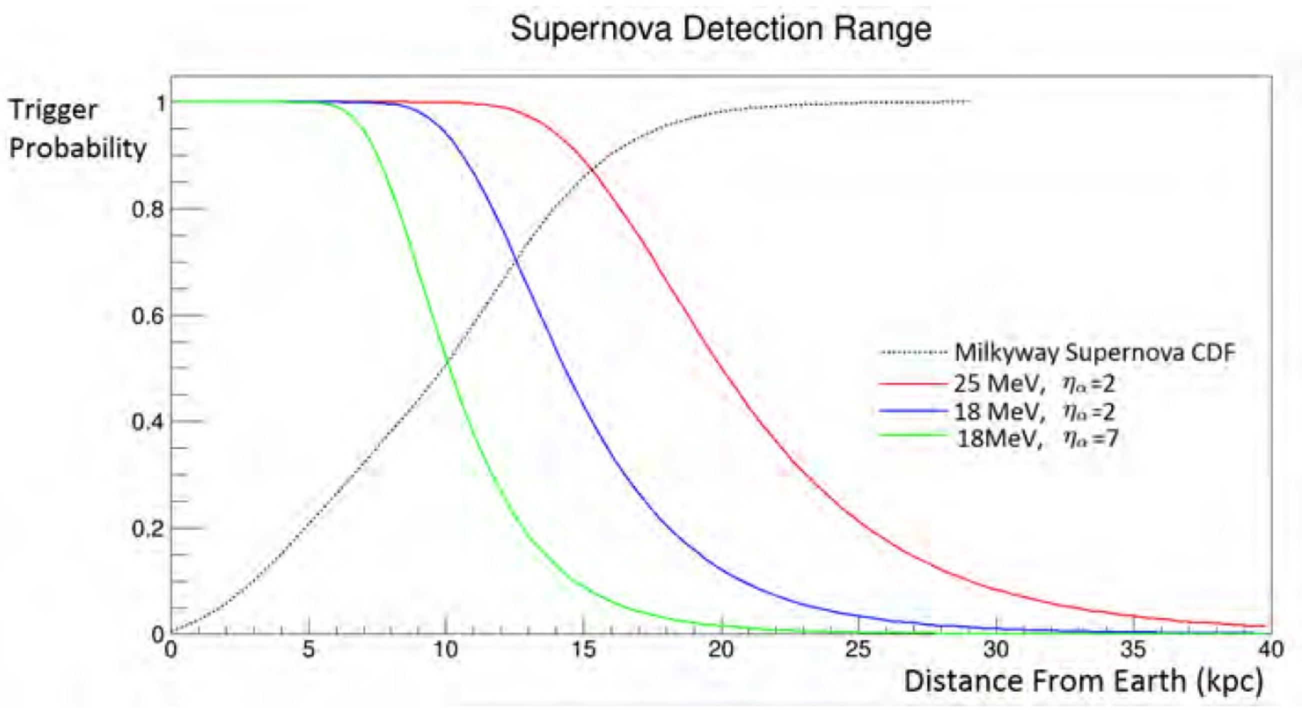
†- cross-sections from Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003)

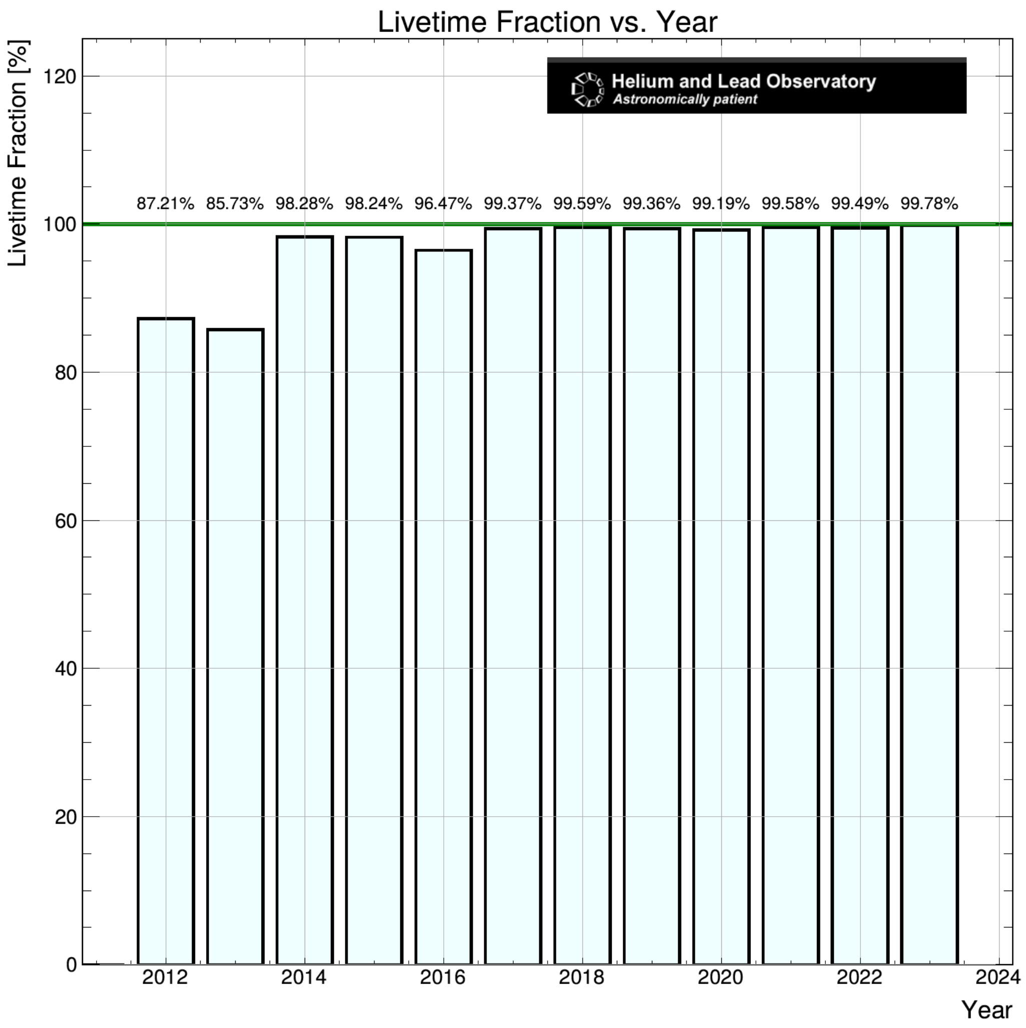
For HALO neutron detection efficiencies of 28% have been obtained in MC studies optimizing the detector geometry, the mass and location of neutron moderator, and enveloping the detector in a neutron reflector.

SNEWS

- Simple burst trigger
  - N events, above an ADC threshold, within a time window (N, E, Δt)
  - For (N, E, Δt) = (3, 400, 2)
    - Classify burst and send email to burst subscribers (< 2 emails per day on average)
      - Spallation or SF if burst duration < 1 ms and energy distribution compatible with expectations
      - Coincidence if compatible with random coincidence of neutron-like events
        - Occurred 180 times in last 444 days
      - Other if energy distribution incompatible with expectations for neutrons
        - Infrequent, often associated with activity near detector
  - For (N, E, Δt) = (4, 400, 2)
    - Classified as SN Candidate and SNEWS alert sent with seconds of latency
      - Roughly 1 / yr, last one 198 days ago
    - HALO, through SNEWS, able to provide very low latency “save your data” alert to any interested detector
- Connected to SNEWS since October 8, 2015 and active in SNEWS 2.0

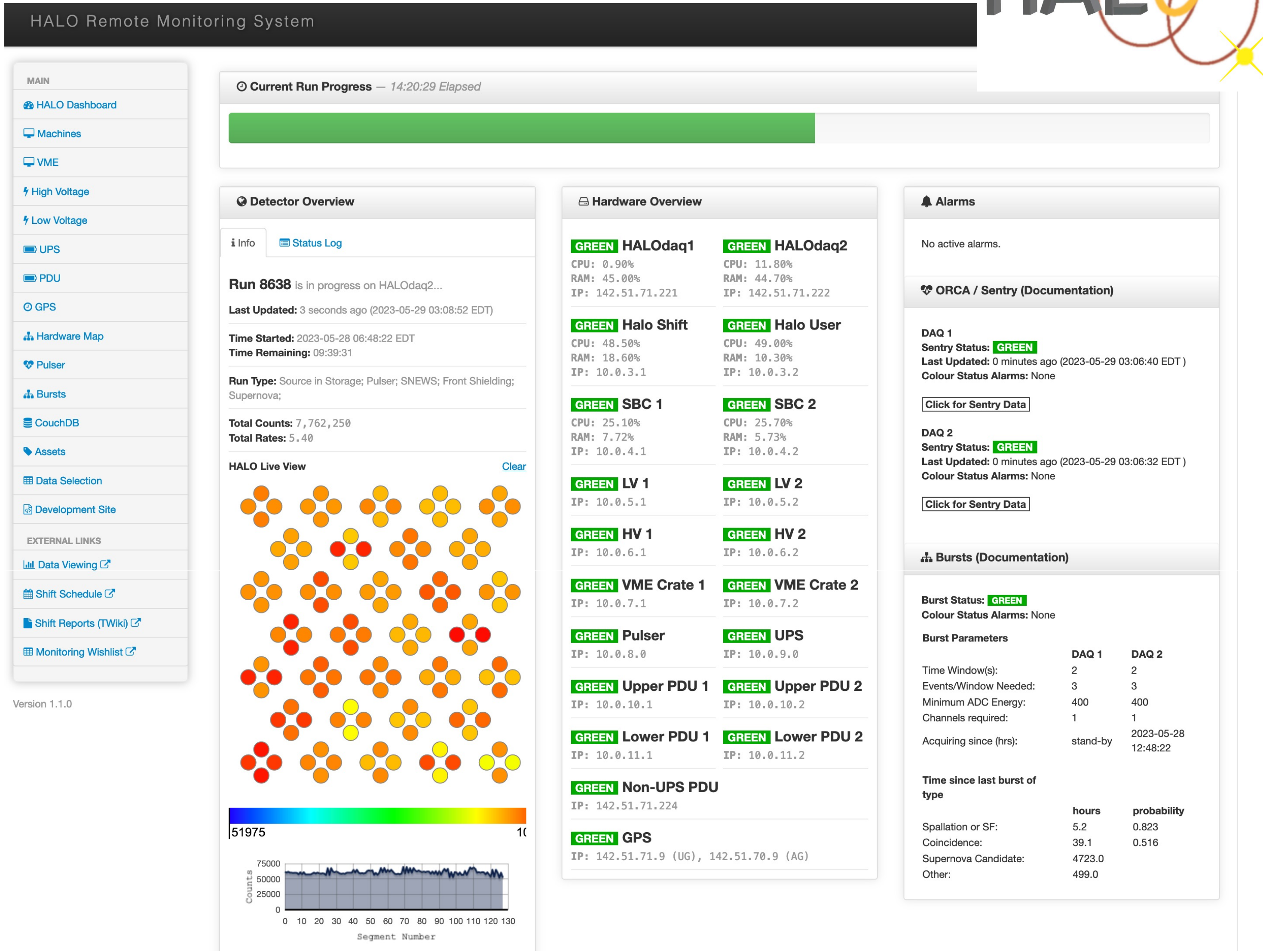
Performance





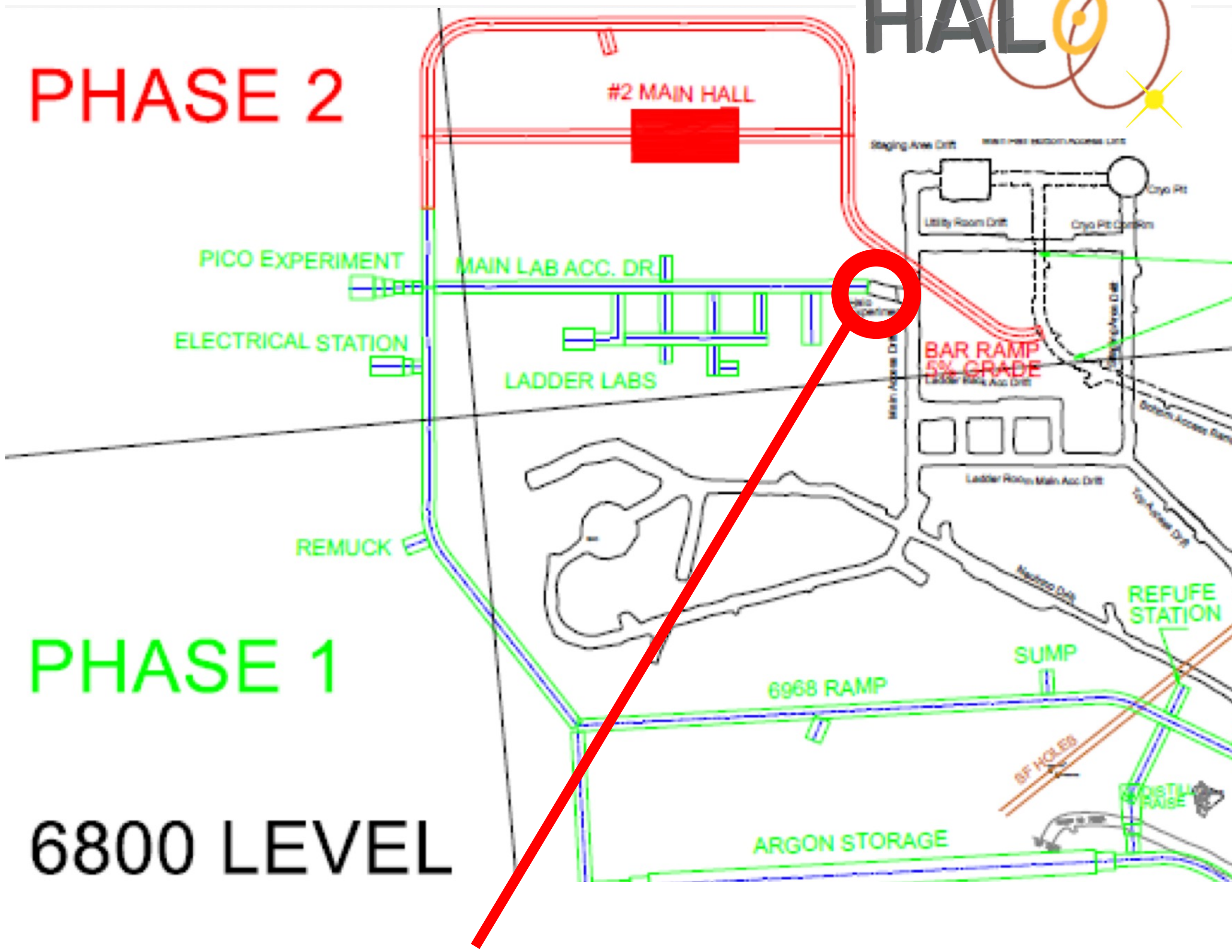
Monitoring

- Well developed monitoring of everything
- Surveyed twice daily by one of group of 15 shift-takers
- Status emails plus alert emails to expert sub-group



Future - HALO

- Continue operations, SNOLAB support minimizing impact of “Laurentian Insolvency”
- Recently renewed computers and UPS, hardware in great shape
- Transitioning to SNEWS 2.0
- Have SNOLAB space allocation until 2028
    - Space renewable but may eventually be limited by lab expansion plans
- Transitioning from single spokesperson to two co-spokespeople
- Real effort going into continuous documentation / knowledge transfer



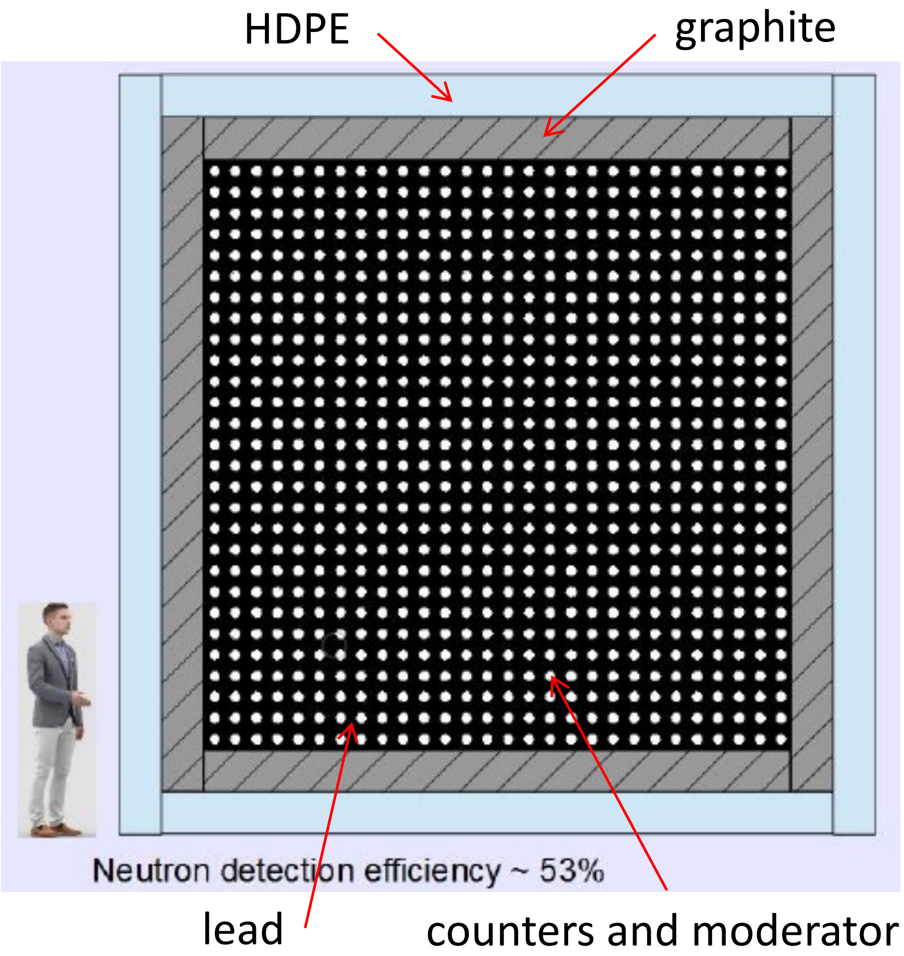
HALO location becomes access to expanded Lab in future (unfunded) expansion scenario

Future – HALO-1kT?

- For HALO at SNOLAB → HALO-1kT at LNGS
  - 79 → 1000 tonnes Pb (OPERA lead)
  - 1465 → 10,000 litre.atm of ^{3}He (DOE?)
  - 28% → >50% n capture eff. (from optimization studies)
  - ~23 times the event statistics of HALO

HALO-1kT Base Design

- lead core 4.33 x 4.33 x 5.5 m^3 with 28 x 28 x 5.5 m array of ^3He neutron counters at 1.16 atm pressure (4300 m total)
- 8 mm thick PS moderator
- up to 30 cm graphite reflector
- up to 30 cm HDPE shielding
- reflector and shielding require further optimization once we have conceptual mechanical design for superstructure
- Control of background in neutron counters
  - Only significant technical question
  - Likely path forward identified



Simulation Studies

- Focus on optimizing neutron capture efficiency
- constrain to 10,000 litre.atm of ^{3}He; 1000 tonnes of lead; 5.5 m depth of lead volume
- explore various geometrical effects
  - overall shape
  - number of detectors (^{3}He pressure varies inversely)
  - proportional tube wall materials / thicknesses
  - moderator materials / thicknesses
  - presence / absence / thickness / composition of reflector layer
  - thickness of HDPE shielding
  - More
- Achieve 50-55% neutron capture efficiency for range of parameters

But...

- ~2 year delay in funding in Canada due to change of government and delayed commitment to matching funds
- Then was being seconded to an administrative position when Laurentian Insolvency “advanced my retirement” when the Physics Department was closed
- HALO-1kT at LNGS lost steam through these past 3-4 years...
- Need for new blood and fresh leadership is clear
- More HALO-1kT R&D has been done
- I would be thrilled to assist significantly in discussions and efforts to push forward with HALO-1kT at LNGS

Fine / Grazie