Helium and Lead Observatory for supernova neutrinos

NuInt12

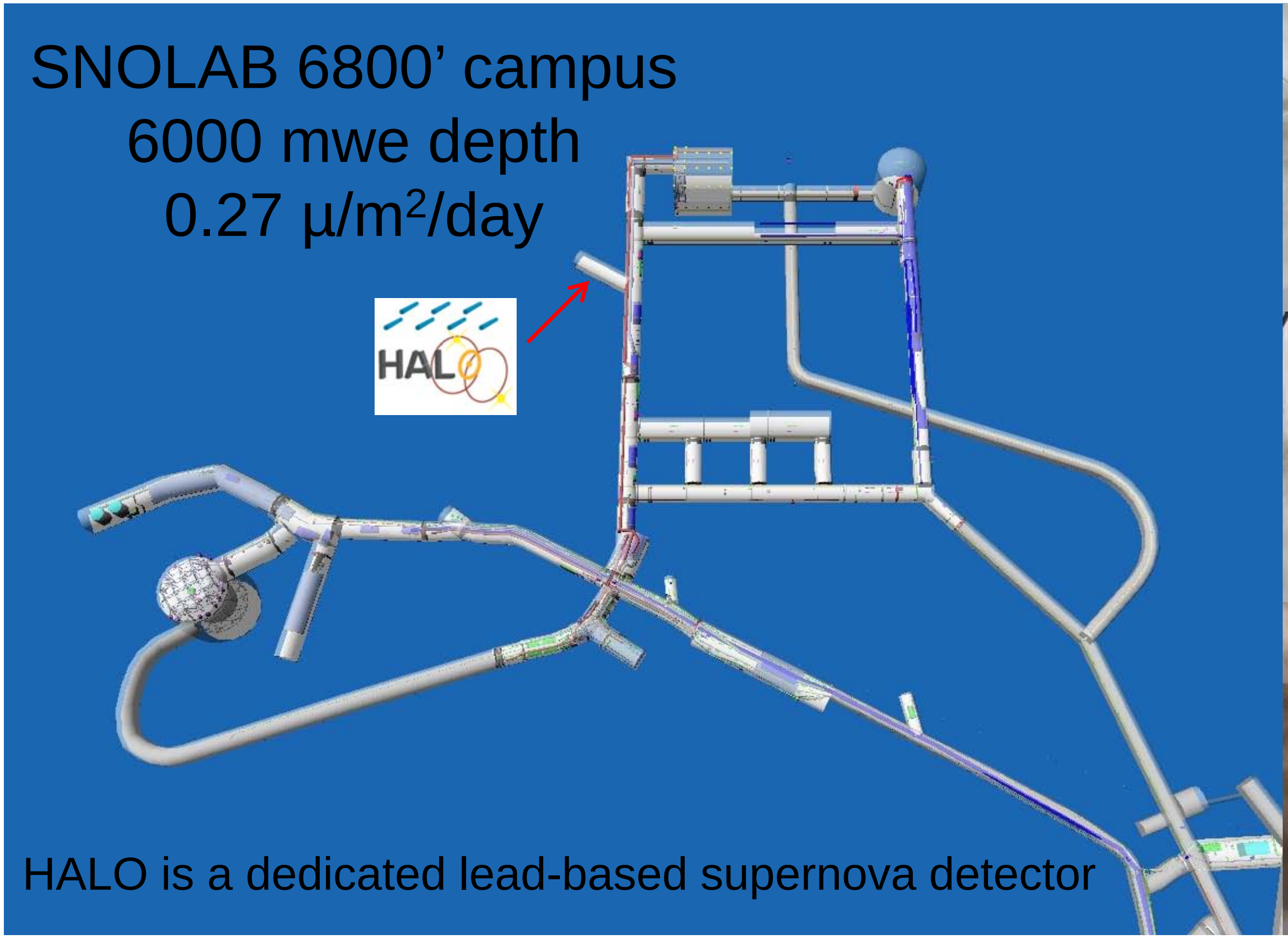
Rio de Janeiro

October 23, 2012

Clarence J. Virtue

HALO at SNOLAB

SNOLAB 6800' campus
6000 mwe depth
0.27 μ/m^2/day



HALO is a dedicated lead-based supernova detector

HALO at NuInt 2012?

- The response of supernova detectors in general is dominated by well-known standard model x-sections to the extent that the “target” is protons and electrons
- Nuclear targets are now being pursued and do require reliable low energy x-sections

Talk Outline

- Preamble, the trouble with supernovae
- Supernovae and the scientific impact
- HALO: sensitivity and rates
- Status
- Future plans

The Trouble with Supernovae

- Very frequent in our universe (1 per second)
- Current and next generation terrestrial supernova detectors only see supernovae within our galaxy (tiny part of the universe)
- So.... The galactic supernova rate is estimated at

3 +/- 1 per century

Worse than that....

For any given supernova detector, but let's take SNO/SNO+ as a non-representative example, the project cycles are problematic….

- 6 years from conception to funding
- 8 years to construct (~$70M)
- "Ran" for 8 years (~$4M/year), but
  - Was only "on" for 5.5 years of the 8
  - Was calibrating for ~25% of those 5.5 years
- Was shutdown in November 2006
- 6 years later still isn't back on....

Which is to say...

- While the odds on a galactic SN in your lifetime are pretty good, the chances of seeing it with a detector like SNO are far from guaranteed.
- So.... there's a niche for low cost, low maintenance, long lifetime, dedicated supernova detectors
- Also, for next generation neutrino detectors costs go up as the energy threshold goes down and there is a risk that supernova sensitivity will be degraded in order to save costs

Supernova neutrinos – First order expectations

- Approximate equipartition of neutrino fluxes
- Several characteristic timescales for the phases of the explosion (collapse, burst, accretion, cooling)
- Time-evolving ν_e, $\bar{\nu}_e$, $\nu_{\text{"}\mu\text{"}}$ luminosities reflecting aspects of SN dynamics
  - Presence of neutronization pulse
  - Hardening of spectra through accretion phase then cooling
- Fermi-Dirac thermal energy distributions characterized by a temperature, T_ν, and pinching parameter, η_ν

$$\phi_{FD}(E_\nu) = \frac{1}{T_\nu^3 F_2(\eta_\nu)} \frac{E_\nu^2}{\exp\left(E_\nu/T_\nu - \eta_\nu\right) + 1}$$

- Hierarchy and time-evolution of average energies at the neutrinosphere

$$T(\nu_{\text{"}\mu\text{"}}) > T(\bar{\nu}_e) > T(\nu_e)$$

- ν-ν scattering collective effects and MSW oscillations

Put another way...

An observed SN signal potentially has information in its:

- The time evolution of the luminosities
- The time evolution of the average energies
- The values of the pinching parameters
- Deviation from the equiparition of fluxes
- Modifications of the above due to ν-ν scattering collective effects and MSW oscillations

What is to be learned?

- Astrophysics
  - Explosion mechanism
  - Accretion process
  - Black hole formation (cutoff)
  - Presence of Spherical accretion shock instabilities (3D effect)
  - Proto-neutron star EOS
  - Microphysics and neutrino transport (neutrino temperatures and pinch parameters)
  - Nucleosynthesis of heavy elements
- Particle Physics
  - Normal or Inverted neutrino mass hierarchy, θ_{13}
  - Presence of axions, exotic physics, or extra large dimensions (cooling rate)
  - Etc.

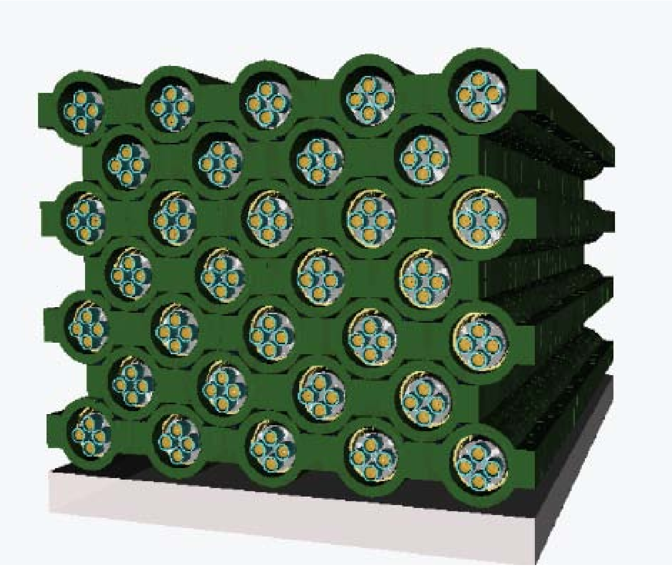
HALO - a Helium and Lead Observatory

A "SN detector of opportunity" / An evolution of LAND – the Lead Astronomical Neutrino Detector, C.K. Hargrove et al., Astropart. Phys. 5 183, 1996.

"Helium" – because of the availability of the ^{3}He neutron detectors from the final phase of SNO

+

"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



HALO is using lead blocks from a decommissioned cosmic ray monitoring station

The HALO Collaboration

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DigiPen INSTITUTE OF TECHNOLOGY
TECHNISCHE UNIVERSITÄT DRESDEN
Duke UNIVERSITY
Laurentian University Université Laurentienne
Los Alamos NATIONAL LABORATORY
UMD DULUTH
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
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- Anne-Mareike Chu – TU Dresden
- Nikki Sanford – Duke University
- Andre-Philippe Olds – Laurentian U.

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NSERC CRSNG   NSF

halo.snolab.ca

Comparative ν-nuclear cross-sections

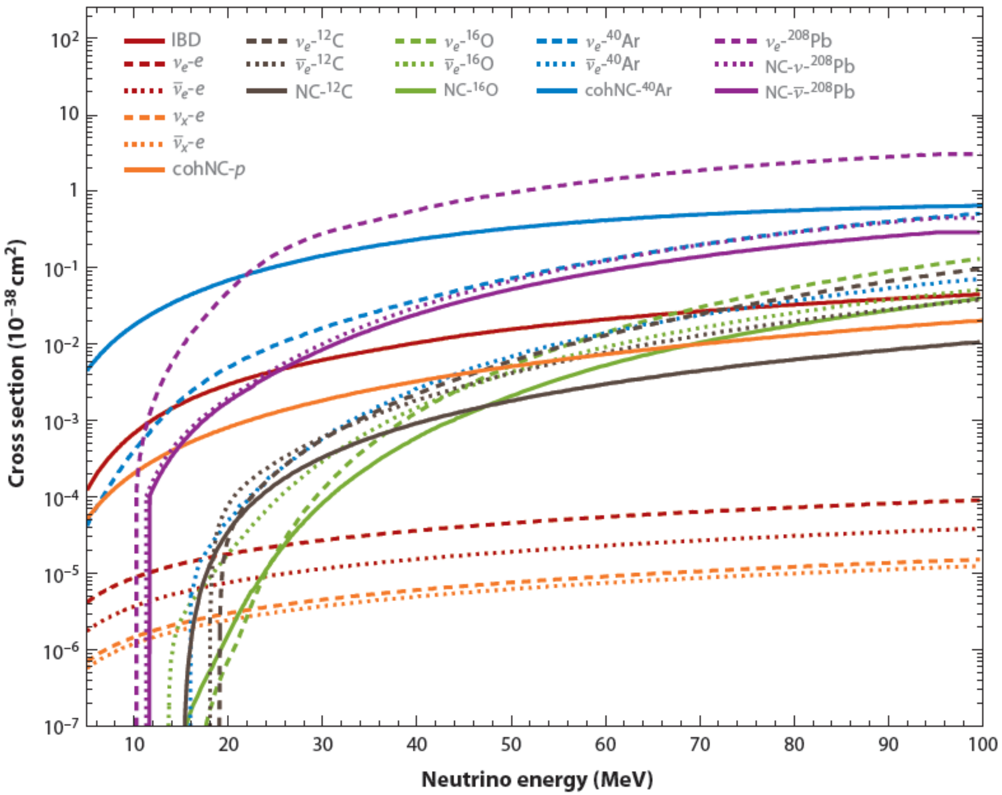
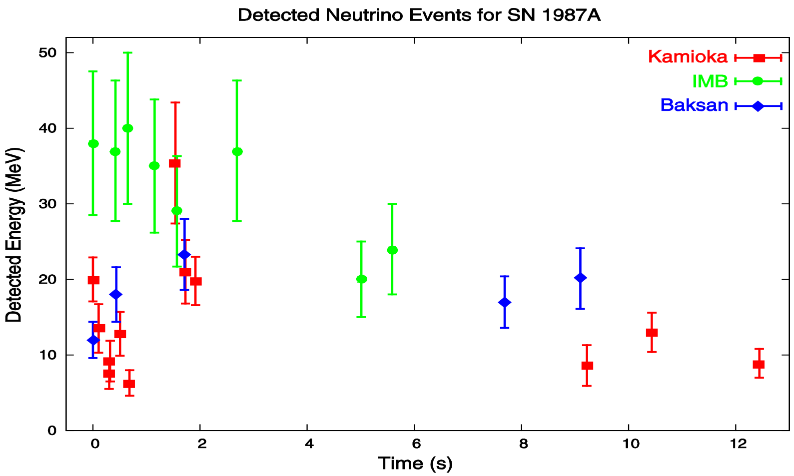


Figure 2

Cross sections per target for relevant interactions. See http://www.phy.duke.edu/~schol/snowglobes for references for each cross section plotted. Abbreviations: IBD, inverse β decay; NC, neutral current.

Thresholds
NC 1n 7.4 MeV
CC 1n 10.7 MeV
NC 2n 14.4 MeV
CC 2n 18.6 MeV



Kate Scholberg
SNOwGLoBES

Pb nuclear physics

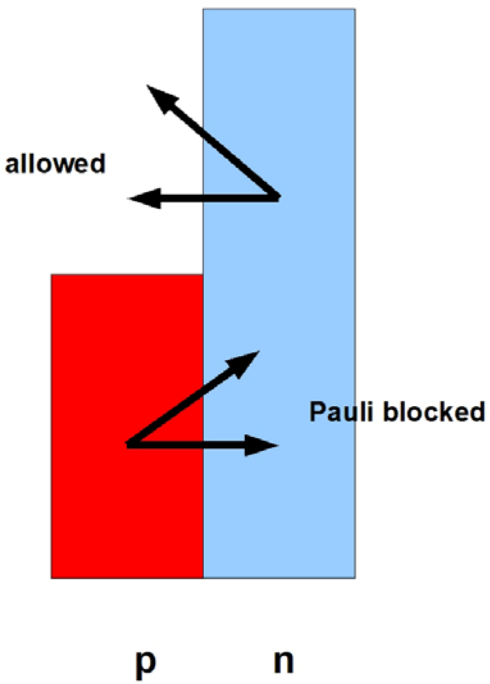
- High Z increases ν_e CC cross-sections relative to $\overline{\nu}_e$ CC and NC due to Coulomb enhancement.
- CC and NC cross-sections are the largest of any reasonable material though thresholds are high
- Neutron excess (N > Z) Pauli blocks

$$\overline{\nu}_e + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n}$$

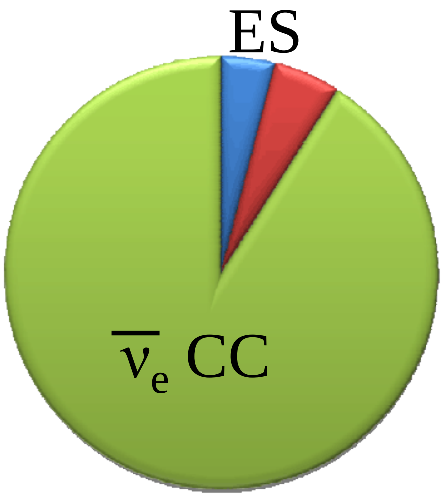
  further suppressing the $\overline{\nu}_e$ CC channel
- Results in flavour sensitivity complimentary to water Cerenkov and liquid scintillator detectors

Other Advantages

- High Coulomb barrier → no (α, n)
- Low neutron absorption cross-section (one of the lowest in the table of the isotopes) → a good medium for moderating neutrons down to epithermal energies
- Dense → compact detector, reduced need for shielding or even self-shielding

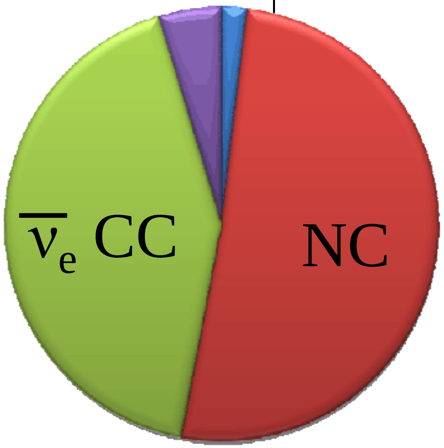


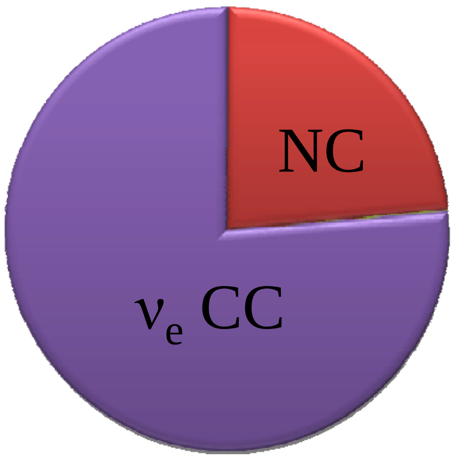
Flavour Sensitivities (subject to neutrino temperatures and thresholds)



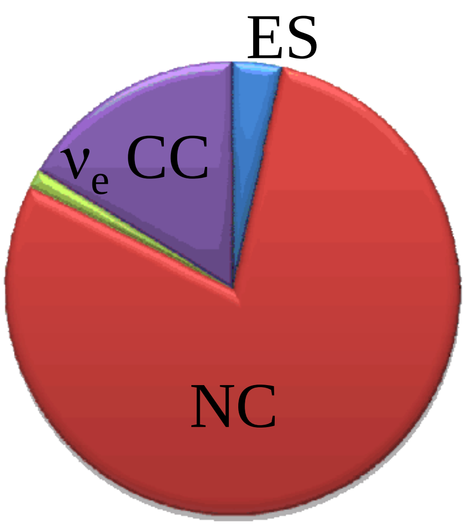
Water
Cherenkov

Liquid
Scintillator





Lead

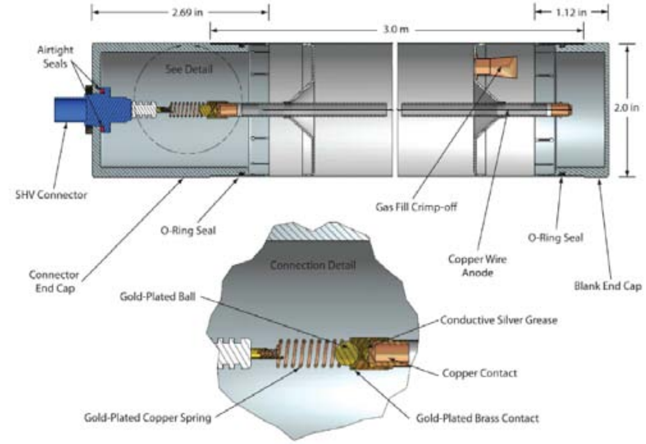


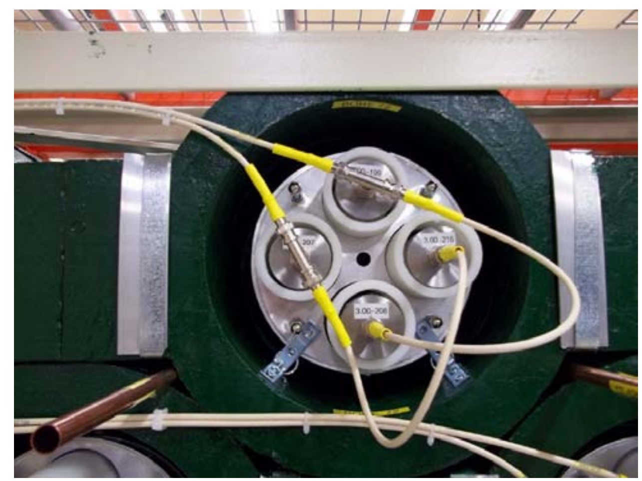
Liquid
Argon
(needs updating
for large θ_{13})

Iron

Neutron detection in HALO

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



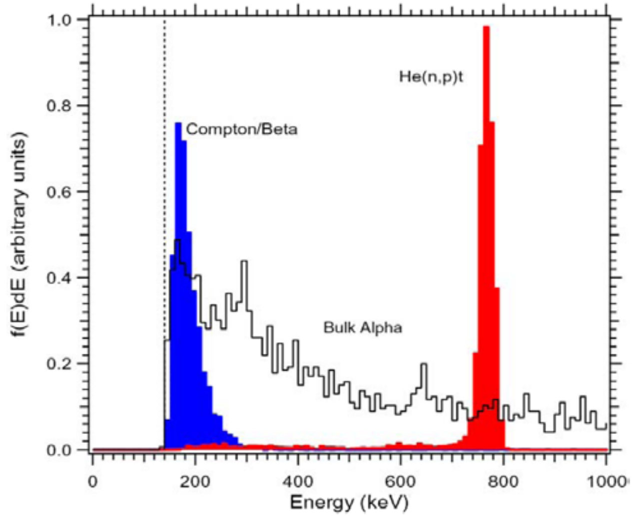


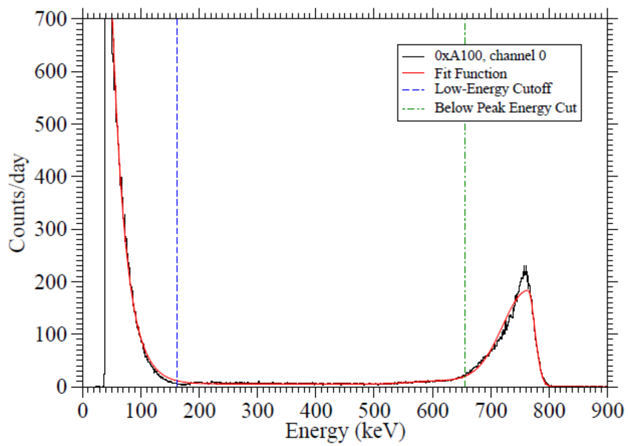
Neutron detection in HALO

- Neutron detection via

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

- 764 keV FE peak plus LE tail due to wall effects
- α's present at rate of ~20 events per day for the entire array
- Compton and beta events at low energies, especially with substantial lead shielding
- Background n in room at level of 4000 fast plus 4000 thermal per m^2 per day.
- Cosmic muons < 2 per day
- Intrinsic tritium rate (18.6 keV endpoint) above 12 keV threshold ~10 Hz per DAQ channel
- Current neutron rate in HALO with incomplete shielding ~0.1 Hz
- ~ zero background during a SN burst





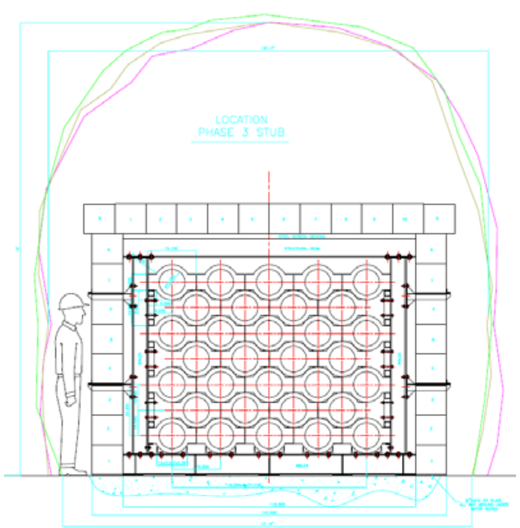
Supernova signal in HALO

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†,

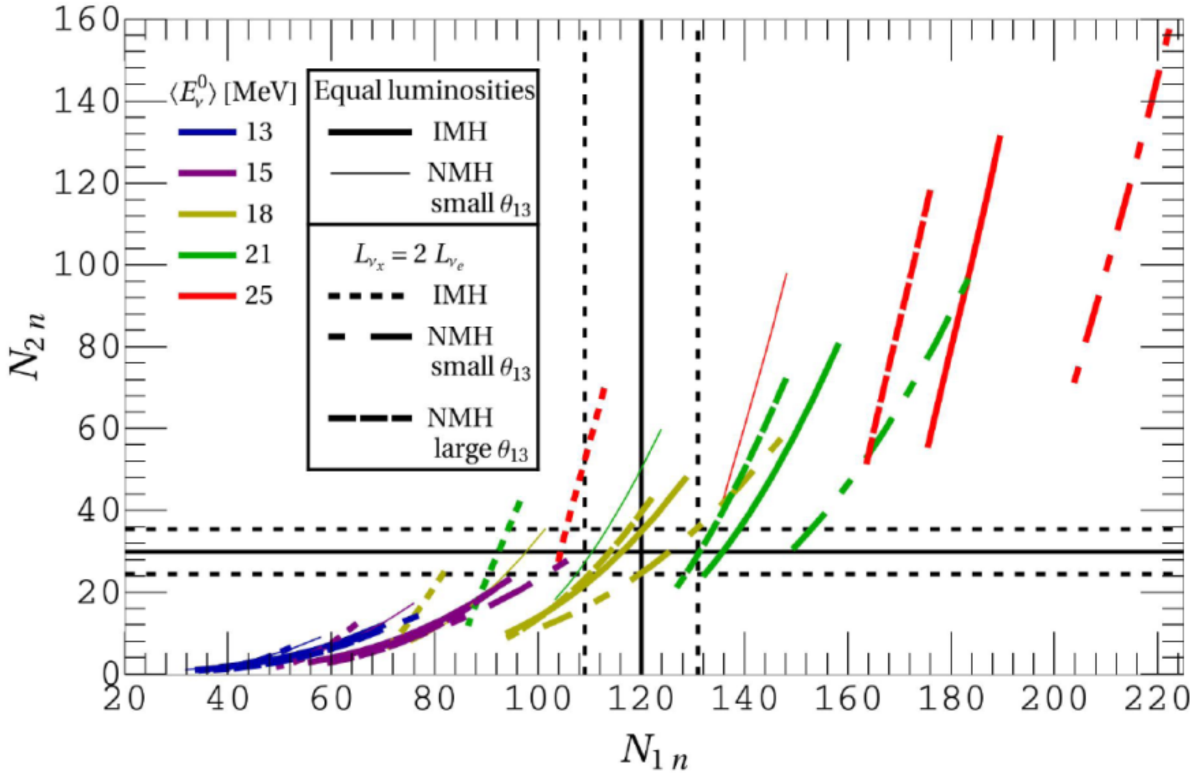
- Assuming FD distribution with T=8 MeV for ν_μ's, ν_τ's.
- 68 neutrons through ν_e charged current channels
  - 30 single neutrons
  - 19 double neutrons (38 total)
- 20 neutrons through ν_x neutral current channels
  - 8 single neutrons
  - 6 double neutrons (12 total)

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

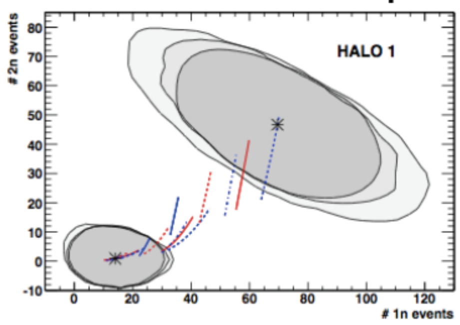
†- cross-sections from Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003)

For HALO neutron detection efficiencies of 50% 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.

Sensitivity to neutrino energy

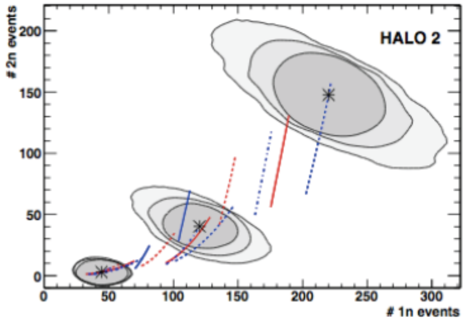


5 kpc



ε = 40%,50%,60%

10 kpc



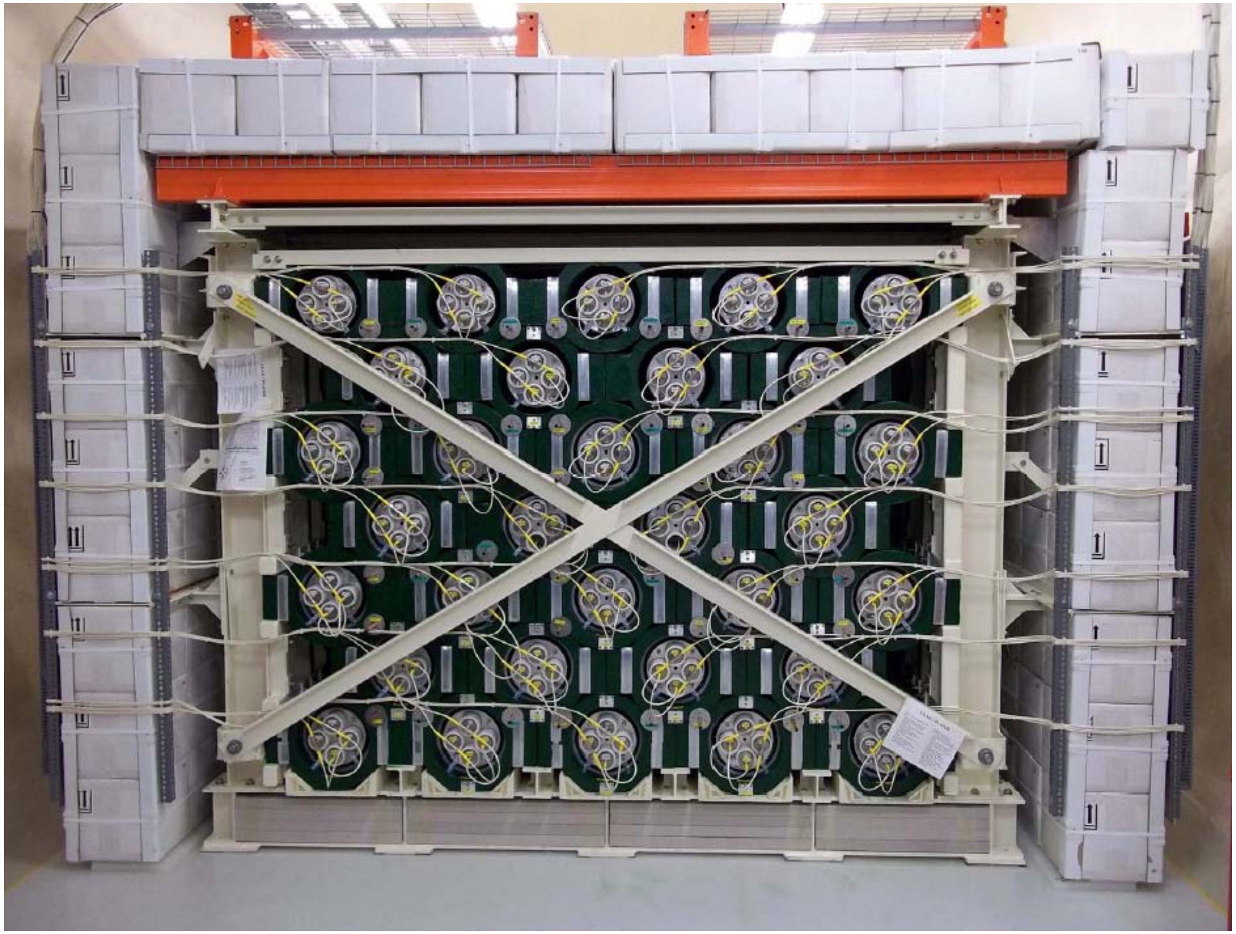
ε = 40%,60%,80%

Distinct 1n and 2n emission thresholds in lead provide the possibility to measure neutrino temperatures and pinching parameters. N_{1n} and N_{2n} per kT from Vaananen D, Volpe C., *J. Cosmol. Astropart. Phys. 1110:019 (2011)*

March 2012 APS, K. Scholberg.

Status today

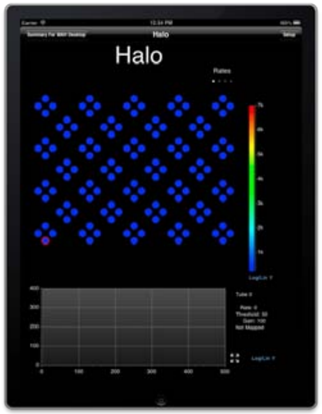
- 4/5th of shielding in place
- Cabling complete
- Readout complete
- HV on all channels and full detector being read-out since May 8th 2012.
- Daily shift-taking since July 27th
- Remote control, monitoring and alarm (CMA) capability under active development
- Participating in gps time provisioning for SNOLAB
- Upgrade of electronics pending
- Counter characterization essentially finished
- Calibration with ^{252}Cf happens next



Future Plans - HALO

Near-term Plans – completion of HALO

- shielding complete shortly
- Develop remote CMA
- Calibrate n capture efficiency
- Participation in SNEWS in 2013



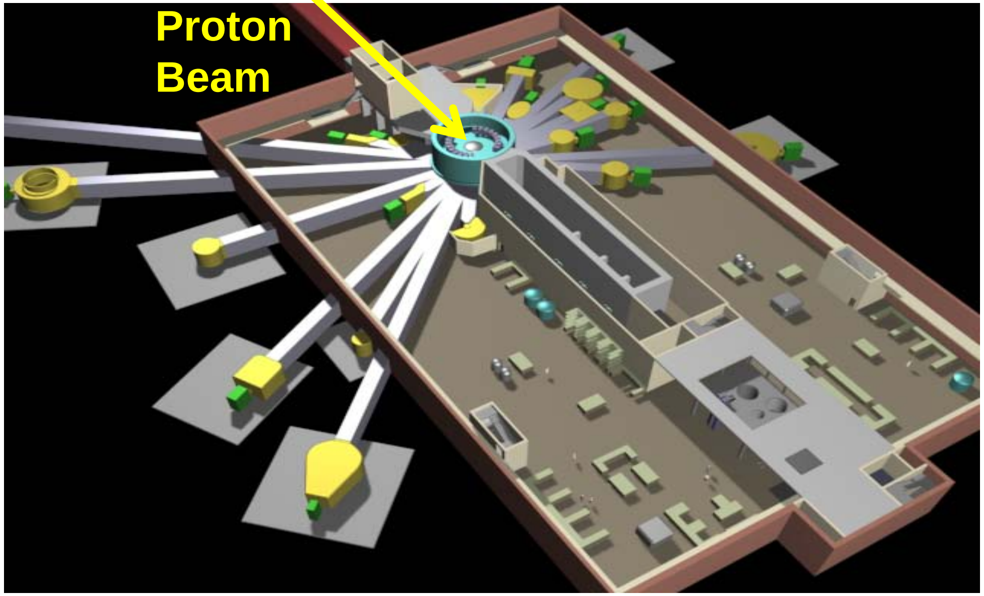
Longer-term Plans

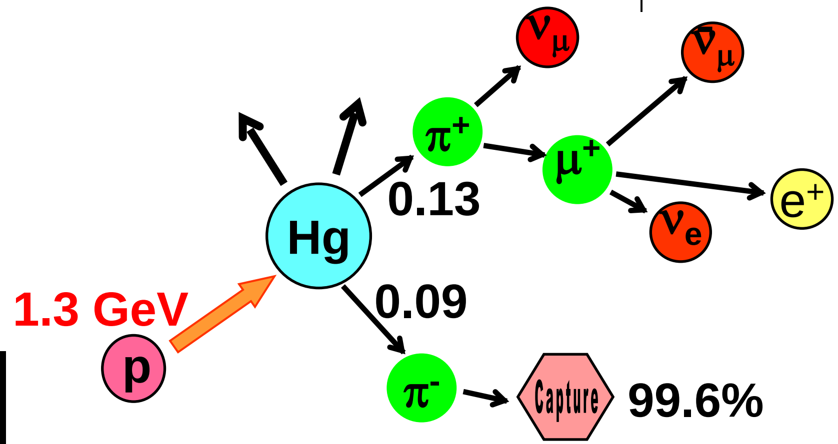
- Be astronomically patient
- Tag cosmic muons and measure neutron multiplicity in muon spallation events on lead

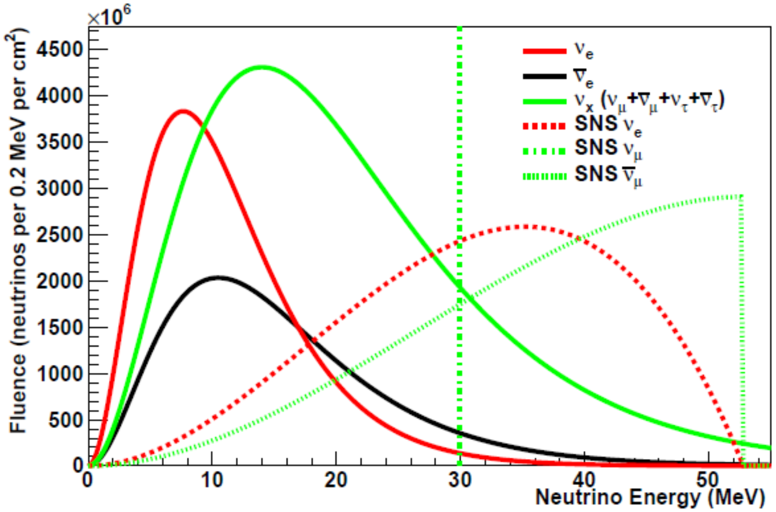
  (because we can – searching for a day job)

Future Hopes – ν-Pb x-sections

- At SNS at ORNL
  - Point source of $\nu_\mu, \bar{\nu}_\mu, \nu_e$ at ~2e22 per year each, with time structure
  - Reasonably matched to SN energies







Future Hopes – kT "HALO" ?

- Development of physics case and detector design for a kT class lead-based detector
- Need still to establish the scalability of the technology without ^{3}He, ie. substitute neutron detection technology (^{7}Li or ^{10}B based)
- Growing collaboration..... This is an open invitation! ☺