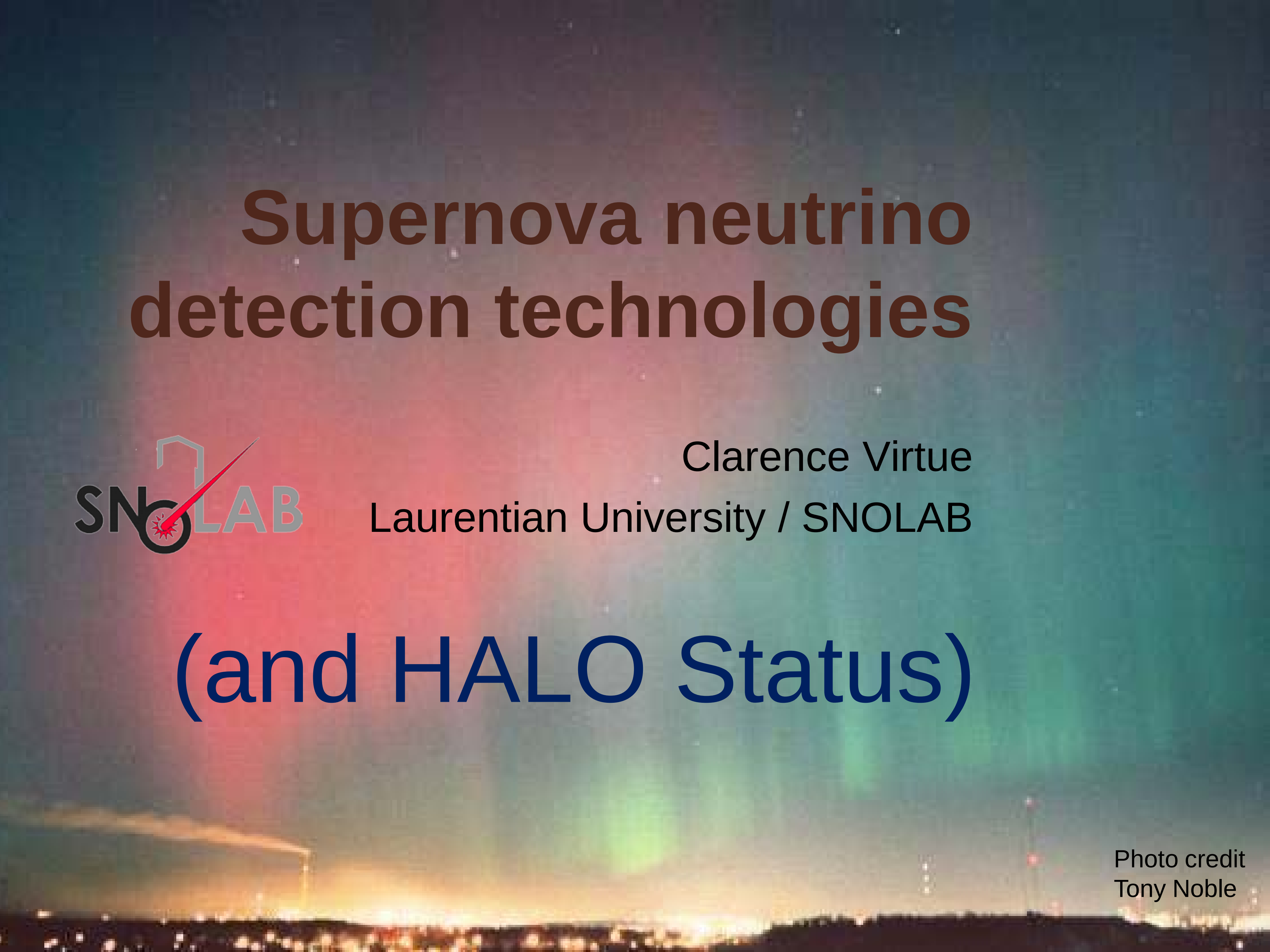


Supernova neutrino detection technologies

Clarence Virtue
Laurentian University / SNOLAB

(and HALO Status)

Photo credit
Tony Noble

Organization of this talk

- Introduction
  - Generalities
  - What, why and how
- Targets
  - Electrons
  - Protons
  - Nuclei
- Detection technologies
  - Capabilities
  - Comparisons
- HALO update
- Conclusions

Introduction - Generalities

- It is a pleasure to set the stage for this afternoon's series of detector-specific talks
  - Super-K + Gd for SN detection – Makodo Sakuda
  - SN neutrino signal in Icecube – Goesta Kroll
  - SN neutrino detection in Antares – Vladimir Kulikovskiy
  - SN neutrinos in liquid scintillator detectors – Aldo Ianni
  - SN neutrinos in LVD – Walter Fulgione
  - Coherent scattering for SN neutrinos – Georgios Tsiledakis

Introduction - Generalities

- My objectives are to:
  - examine the SN neutrino signal and comment on the desired sensitivities and capabilities of an ideal SN detector
  - review the coupled aspects of target choice and detection technology
  - Contrast and compare the sensitivities and capabilities of different choices

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-evolving 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

And so....

An ideal detector would do a good job of measuring all of these properties....

Nature has not provided us with such tools!

Let’s examine the motivation for making such measurements before discussing what is possible

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.

What distinguishes SN neutrinos from others?

- Unlike solar, atmospheric, reactor or geo-neutrinos... SN neutrinos are not always there
- Unlike accelerator neutrinos we don’t know when they are coming
- Unlike appearance or disappearance experiments the “beam” contains all flavours ~ equally
- The beam is a primary beam (not tertiary as for atmospheric or accelerator neutrinos) and the energy spectrum has direct physics content
- The intensity of the beam has a probable value but could differ by more than 2 orders of magnitude
- They have their own characteristic range of energies determined by core collapse physics and SN1987A confirms that we have some understanding of that
- Energies are “thermal” described by Fermi-Dirac function modified by a pinching parameter or chemical potential, at least initially, and are imprinted with further physics processes of great interest

So...

These considerable differences drive the design of a SN detector... Right?

Well... Not really, or not often, most SN detectors were designed for other primary physics objectives.

And some have a lifetime $< 1/f_{GSN}$

How do we detect a SN?

- We can instrument as large a mass as possible, for as long as possible, and watch for a burst of the subtle effects of the neutrino’s weak interactions
- We get to chose the target and the technology
- To date we’ve concentrated almost exclusively on electrons, protons, and PMTs
- Some other nuclear targets are “along for the ride” and only a few others seem worthy of consideration

The ideal SN detector would...

- Be reliable
  - Target and detector would be stable and reliable for decades
    - Low tech
    - Good aging properties → longevity
- Be large and scalable
  - Target and detector technology should be modular and easily expanded
- Have large neutrino cross-sections
  - Very helpful
  - Additionally, secondaries need sufficient mean free paths to permit detection

The ideal detector would...

- Have diverse sensitivities to different reaction channels and the ability to tag those channels on an event-by-event basis
- Be able to measure the energy and direction of the SN neutrinos
- Have low background / noise levels above a threshold that permits reliable SNEWS alerts from the far-side of the galaxy, or much further.
- Be able to record the data without loss from the nearest conceivable SN

There is no ideal detector(!!)

But how do the old standards stack up and where do the others worth considering fit it?

We'll start with electrons, then protons, then the nuclei of potential interest.

Electrons as targets

Elastic scattering (ES)

- Two diagrams – CC & NC
- The observable particle is an electron, detected through Cherenkov effect or scintillation
- All neutrino species participate in NC elastic scattering but only nu_e participates in CC so ES is predominately nu_e sensitive (~87%)
- Strongly forward peaked
- Good statistical reconstruction of SN direction; ES is 3% channel on an isotropic background in water cherenkov detectors
- Energy information is challenging, unfolding energy spectrum is possible
- Detection via Cherenkov radiation is required to extract the direction
- Detection via scintillation has better energy resolution but energy spectrum is flat a featureless
- There is not yet a technology to replace PMTs on the scale of deployment associated with SN detectors

Protons as targets

- Two reactions occur – inverse beta decay (CC), ν-p ES (NC) Beacom et al. Phys. Rev D66 (2002) 033001

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

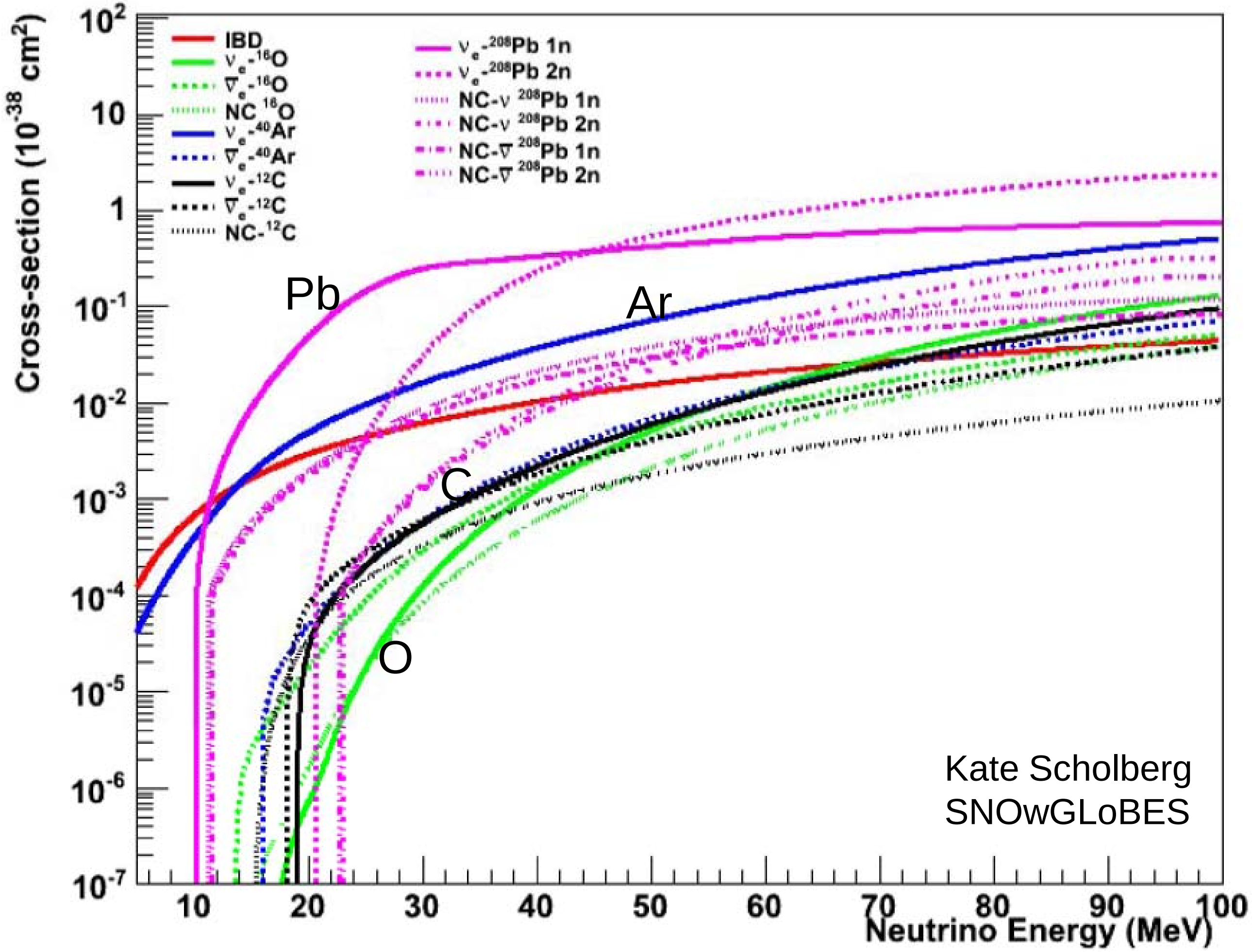
$$\nu_x + p \rightarrow \nu_x + p$$

- Relatively speaking the cross-sections are high for both channels
- Energetic e^+ (plus annihilation gammas) followed by delayed neutron capture is an excellent $\bar{\nu}_e$ tag. Works well in liquid scintillator detectors and water Cherenkov with Gd. (Makodo Sakuda’s talk)

Protons as targets

- IBD has good energy resolution and no directional information
- For liquid scintillator detectors ν-p ES offers the possibility add NC sensitivity to our list of tools for untangling the next galactic supernova
- The challenges are the low proton recoil energies; that these low energies are further quenched; and that the irreducible ^{14}C beta decay spectrum obscures part of the proton recoil spectrum (Aldo Ianni’s talk)

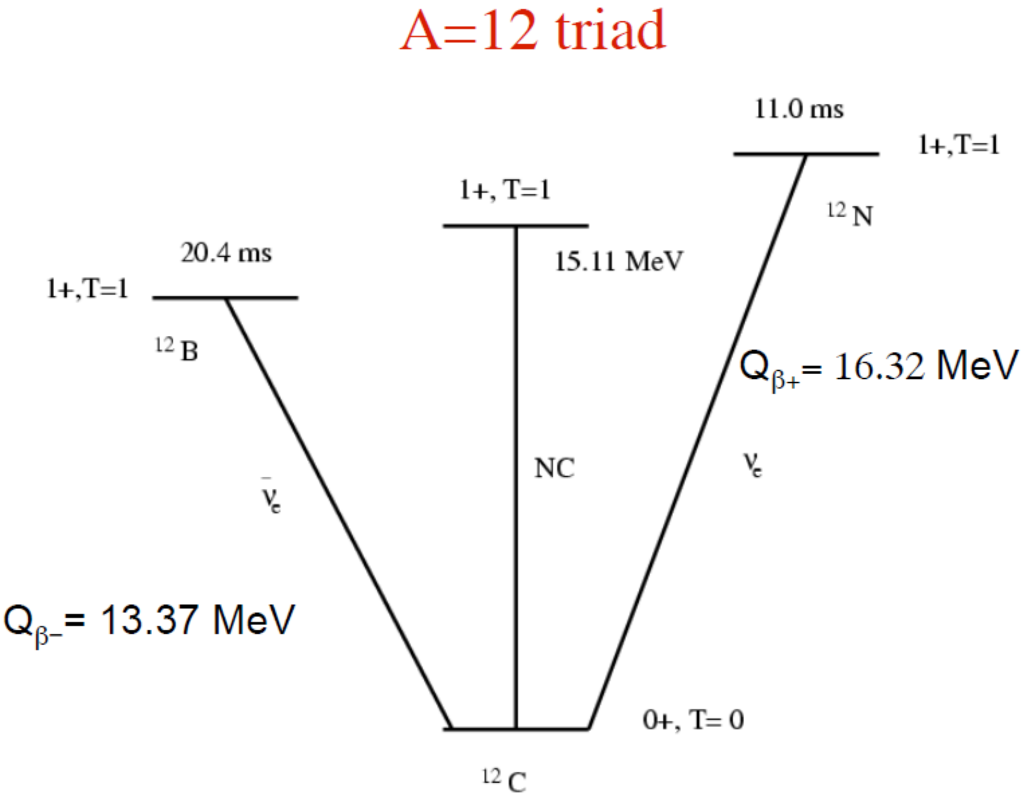
Comparative ν-nuclear cross-sections



Kate Scholberg
SNOwGLoBES

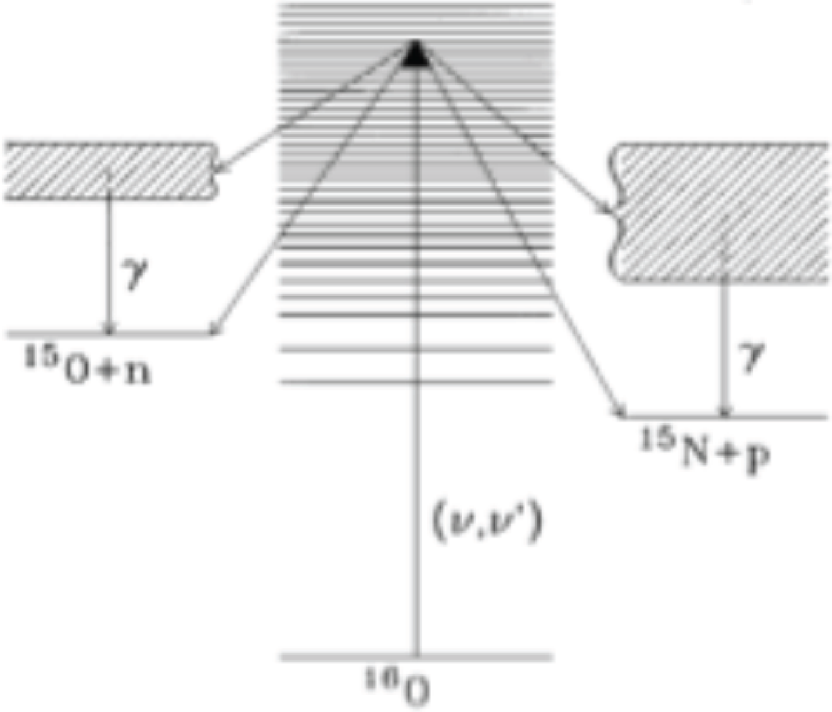
NC and CC excitation of ^{12}C

- Relevant to liquid scintiallators
- NC gives easily resolved 15.11 MeV de-excitation gamma



NC and CC excitation of ^{16}O

- Relevant for water Cherenkov detectors
- Level widths and water Cherenkov resolutions make these NC and CC induced transitions difficult to discern in the data



Supernova neutrino signal in LAr

1. **Elastic scattering** on electrons (**ES**)

$$\overset{(-)}{\nu} + e^- \rightarrow \overset{(-)}{\nu} + e^-$$

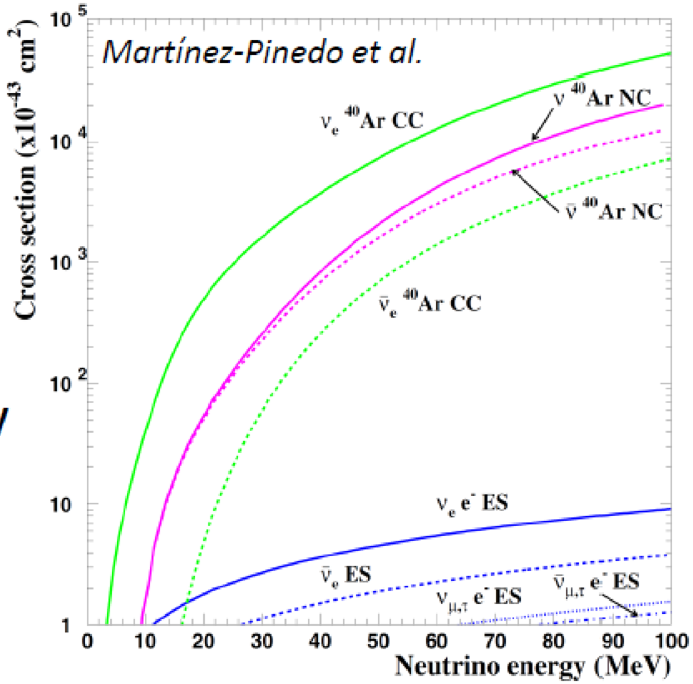
2. **Charged-current** (CC) interactions on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$ **$Q_{\nu eCC}$ = 1.5 MeV**

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$ **$Q_{\bar{\nu} eCC}$ = 7.48 MeV**

3. **Neutral current** (NC) interactions on Ar

$$\overset{(-)}{\nu} + {}^{40}Ar \rightarrow \overset{(-)}{\nu} + {}^{40}Ar^*$$ **Q_{NC} = 1.46 MeV**



Possibility to separate the various channels by a classification of the associated **photons from the K, Cl or Ar deexcitation** (specific spectral lines for CC and NC) or by the **absence of photons** (**ES**)

Pb nuclear physics

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

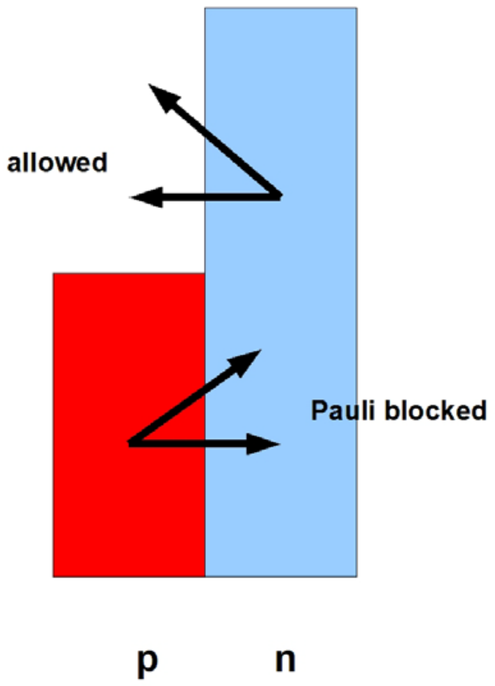
$$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$$

further suppressing the $\overline{\nu}_e$ CC channel

- Results in flavour sensitivity complimentary to water Cerenkov and liquid scintillator detector

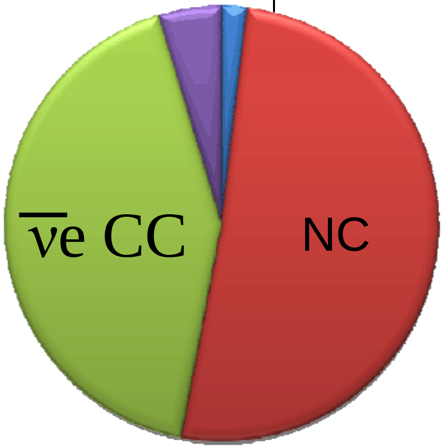
Other Advantages

- High Coulomb barrier → no (α, n)
- Low neutron absorption cross-section (one of the lowest in the table of the isotopes

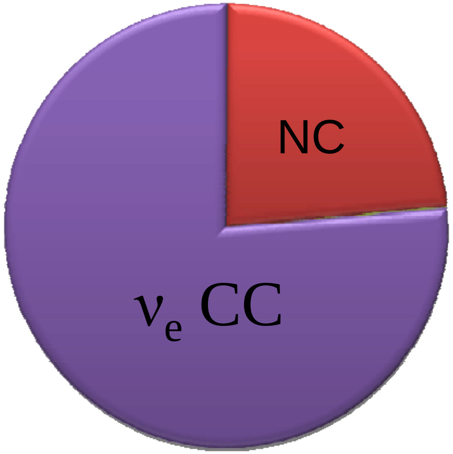


Flavour Sensitivities

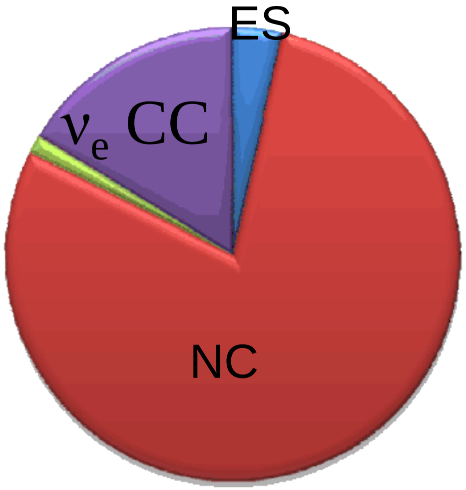
Water
Cherenkov



Liquid
Scintillator



Lead



Liquid
Argon

Iron

Detection Technologies

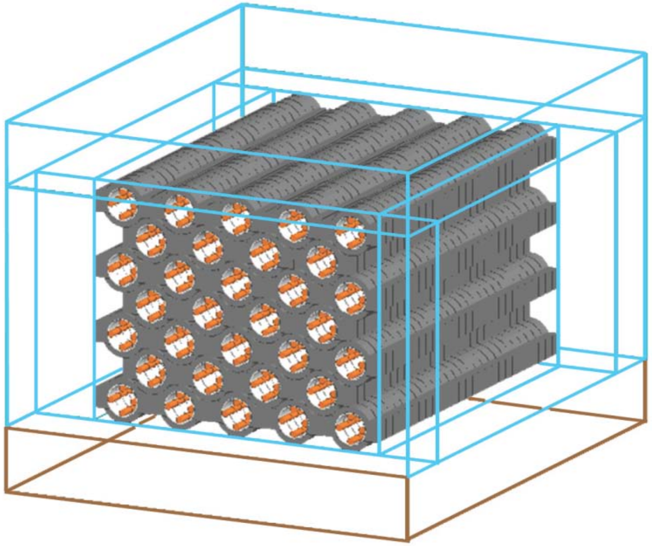
- LAr eg. Icarus
  - Large volume TPC
  - 58,000 channels of readout
  - 150 kV feedthroughs
  - Cryogenic systems
  - Potentially excellent flavour discrimination from topology
  - Future directions: MODULAr 4 x 5 kT modules
    - Increase TPC volume by factor of 8
    - courser readout by factor of 6
    - 200,000 channels, 200 kV feedthroughs
    - T600 from Gran Sasso to Cern after 2012
  - Future directions: Glacier 100 kT

Detection Technologies

- Lead-based detectors
  - ^{3}He is excellent for high capture efficiency, low background
  - National security concerns have dramatically increased cost of ^{3}He to ~$20,000 per gram
  - Large detector likely needs alternate technology
  - Industry actually very active in developing commercially produced alternatives to ^{3}He for Homeland Security applications

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

Goals and Philosophy

Goals

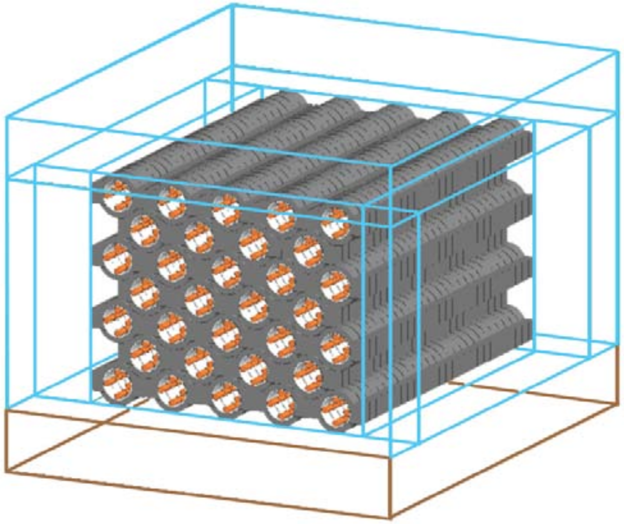
- to provide ν_e (dominantly) and ν_x sensitivity to the SN detection community as soon as possible
- to build a long-term, high livetime dedicated supernova detector
- to explore the feasibility of scaling a lead-based detector to kT mass

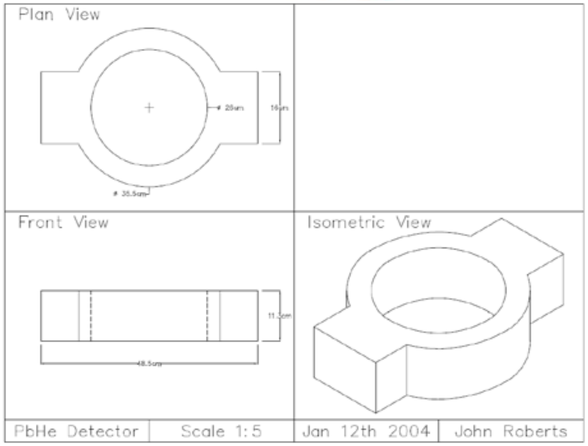
Philosophy

- Achieve these goals by keeping HALO
  - Very low cost
  - Low maintenance
  - Low impact in terms of lab resources

Design Overview

- Lead Array (79 +/- 1% tonnes)
  - 32 three meter long columns of annular Lead blocks
  - 864 blocks total at 91kg each
- Neutron detectors
  - 4 three meter long ^{3}He detectors per column
  - 384 meters total length
  - 200 grams total ^{3}He
- Moderator
  - HDPE tubing
- Reflector (14 tonnes)
  - 15 cm thick graphite blocks
- Shielding (12 tonnes)
  - 30 cm of water





Supernova signal

CC:

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

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

NC:

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

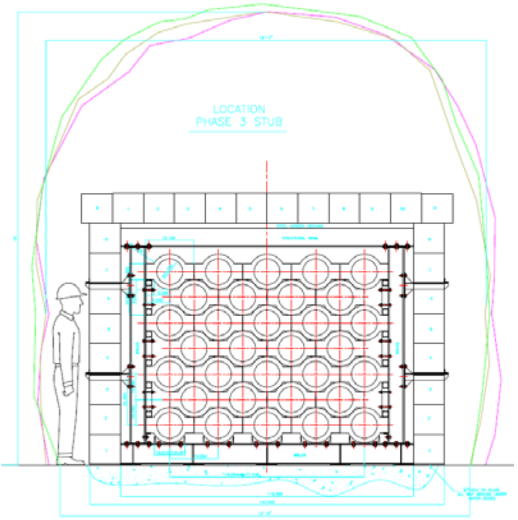
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

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

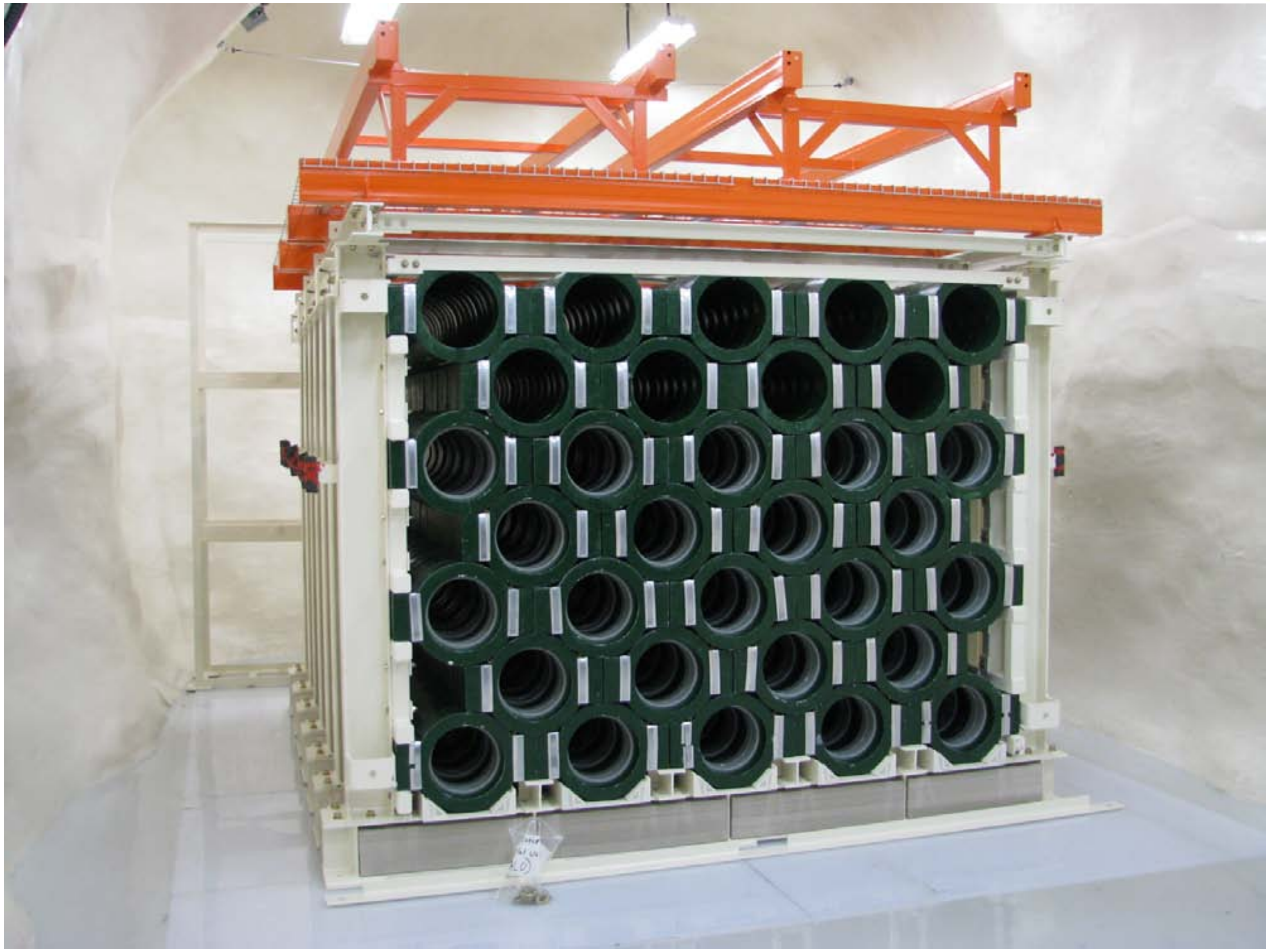
†- cross-sections from Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003)



cf. ~49 events for 600 tonnes of LAr (ES: 8, ν_e : 3, $\bar{\nu}_e$: 38)

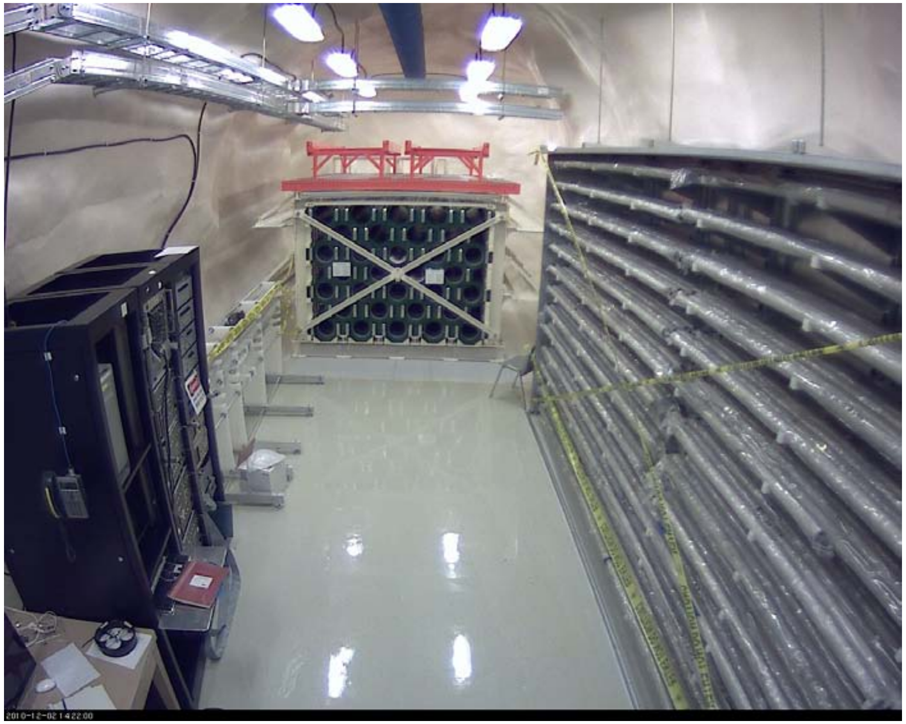
For HALO neutron detection efficiencies of 50% have been obtained in MC studies optimizing the detector geometry, the mass and location of neutron moderator, and enveloping the detector in a neutron reflector.

HALO – March 2010

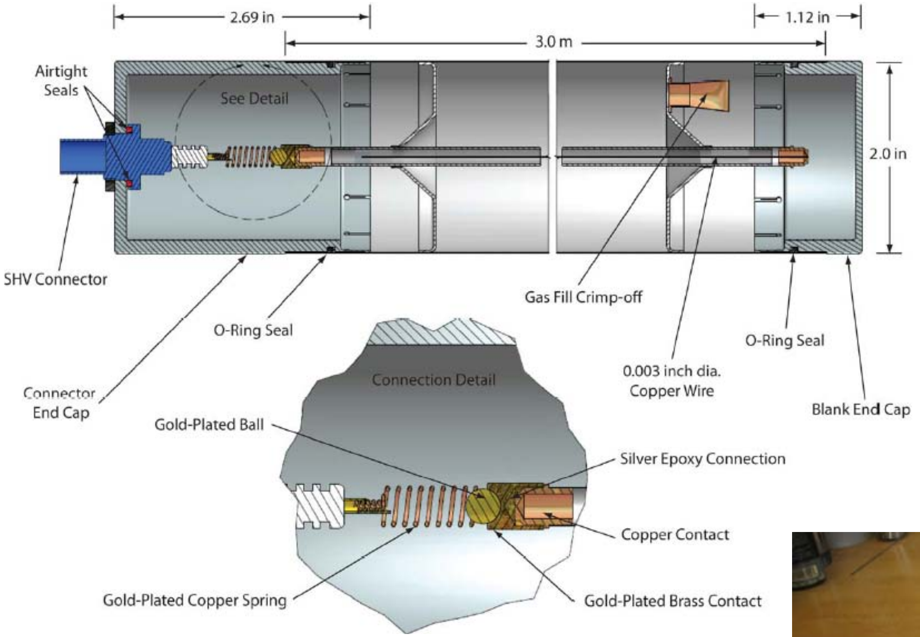


HALO – December 2010

- SNO ^{3}He detectors moved to HALO area (~400 m out of 700 m shown in the storage rack)
- Electronics and test stand also visible



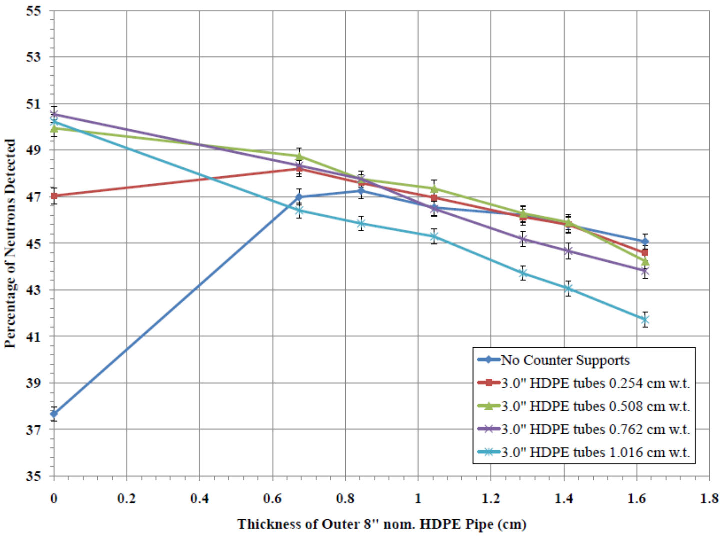
^{3}He neutron detectors

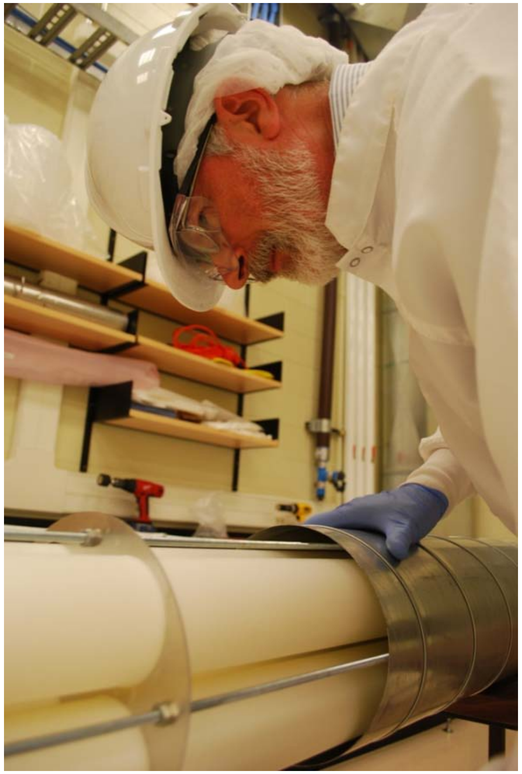


Cutting apart welded sections from SNO installation and adding new endcaps. Six months of careful work!

Moderator

- Design optimized in Monte Carlo
- Last 16 moderator assemblies delivered to underground lab this week





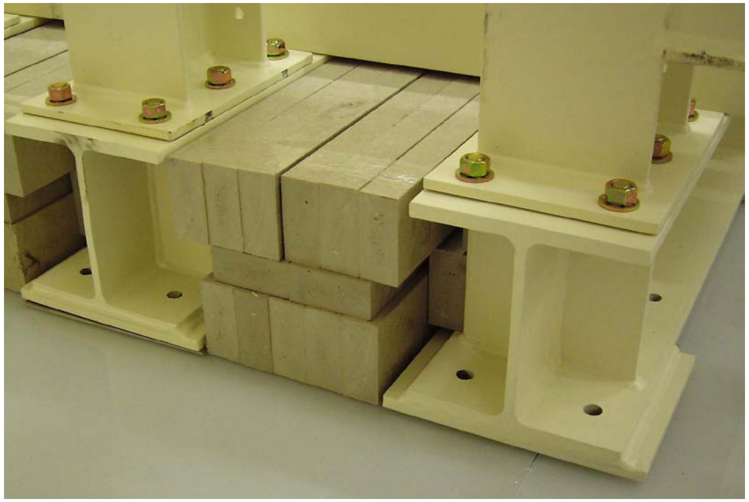
Reflector

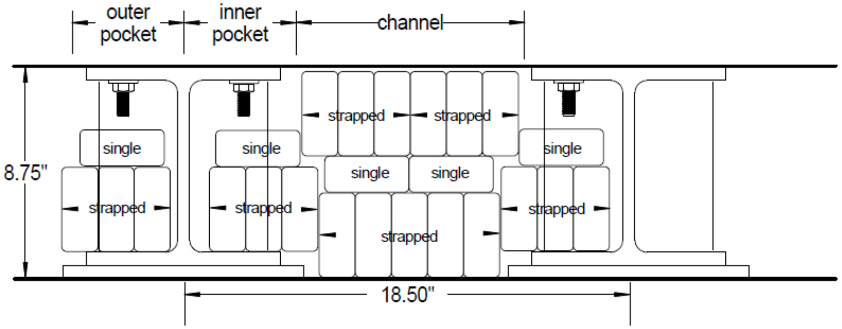
- Presence of the reflector improves the neutron capture efficiency as well as providing additional shielding against external neutrons
- In the event of a supernova the reflector helps to isolate and define the target volume
- Some further simulation work is required to justify the expense; in the meantime the design provides space for the installation of 15 cm of graphite

graphite blocks

Shielding

- PP shielding installed under steel support structure
- 12 tonnes of “water boxes” with voids filled with PS beads (1.3 tonnes) ready for installation

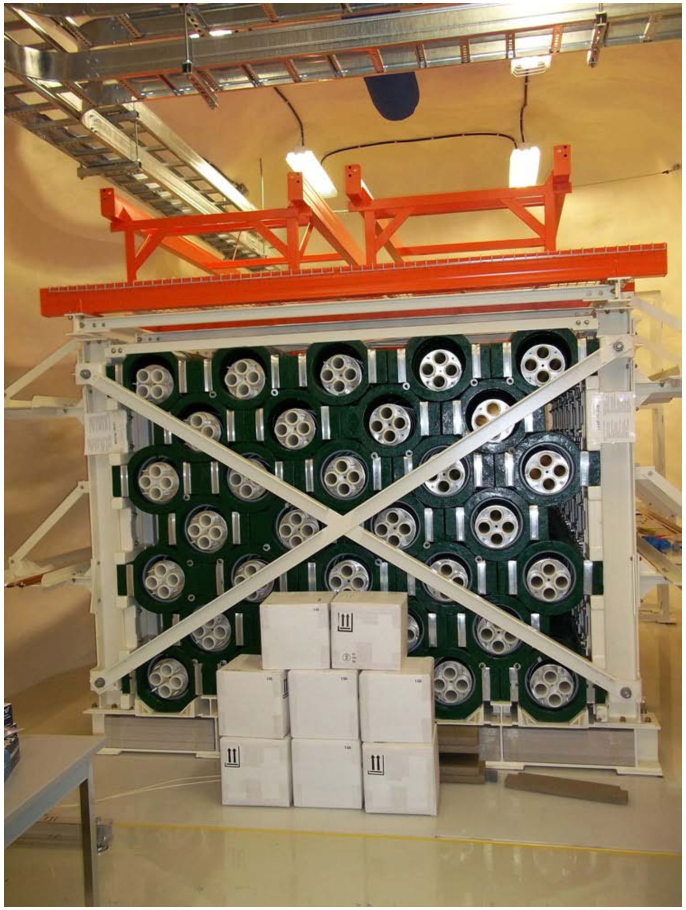




polypropylene shielding concept

Towards a running detector

- As of Wednesday the moderator assemblies were in place in HALO.
- Today 128 ^{3}He detectors will be inserted into place inside the moderator tubes.
- Cabling and readout for 8 channels is in place to allow the start of systematic detector qualification runs
- Full readout and cabling should be in place by the end of September
- Following some benchmark runs without the external shielding the water shielding will be installed



Backgrounds and SNEWS

- A trigger condition of 6 neutrons in a 2 second window gives sensitivity out to ~20 kpc
- A background event rate of 150 mHz from all sources will randomly satisfy the trigger condition once per month. We take this as the target false alert rate for SNEWS
- Fast and thermal neutrons in SNOLAB occur at 4000 and 4100 neutrons/m^2/day respectively
    - Water shielding reduces this to < 100 mHz of detected neutrons in preliminary measurements
    - Water shielding plus graphite reflector provides another factor of 2 decrease in the external neutron rates in MC
- Bulk α contamination in the CVD nickel tubes gives a negligible 22 +/- 1 detected neutrons per day in the whole array
- (α, n) reactions not simulated in the HALO GEANT MC but the threshold in Pb is 15.2 MeV

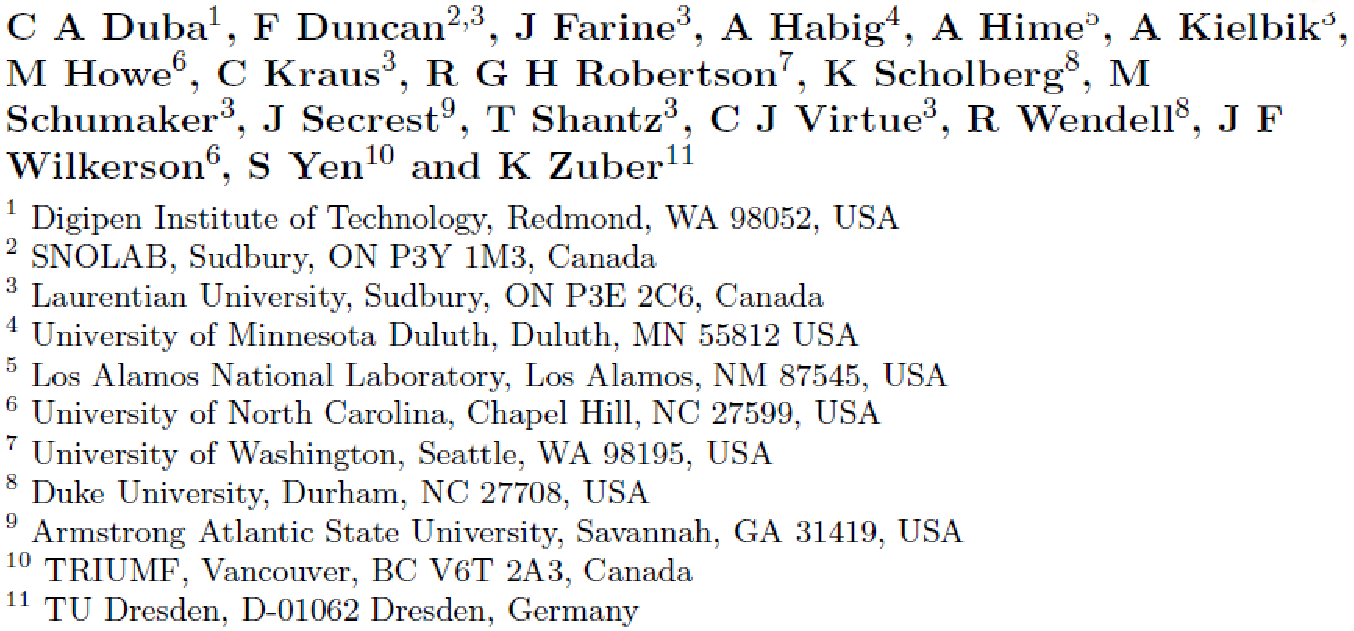
Calibration

- Prior incorporation into HALO each neutron counter will be characterized with a ^{252}Cf source
- The ^{252}Cf source will be placed in multiple locations within and outside the detector to obtain data directly comparable to MC simulations
- The known neutron multiplicity of ^{252}Cf permits a determination of the neutron capture efficiency independent of a precise knowledge of the source strength

Summary

- HALO will be complete and operating in 2011 providing sensitivity to the ν_e and ν_x components of a supernova
- HALO will participate in SNEWS once the behaviour of the detector is well understood
- Experience gained will feed into the design of a next generation detector taking advantage of the scalability of the lead plus neutron detector technology

The HALO Collaboration



C A Duba[1], F Duncan[2,3], J Farine[3], A Habig[4], A Hime[5], A Kielbik[3], M Howe[6], C Kraus[3], R G H Robertson[7], K Scholberg[8], M Schumaker[3], J Secrest[9], T Shantz[3], C J Virtue[3], R Wendell[8], J F Wilkerson[6], S Yen[10] and K Zuber[11]

[1] Digipen Institute of Technology, Redmond, WA 98052, USA
[2] SNOLAB, Sudbury, ON P3Y 1M3, Canada
[3] Laurentian University, Sudbury, ON P3E 2C6, Canada
[4] University of Minnesota Duluth, Duluth, MN 55812 USA
[5] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[6] University of North Carolina, Chapel Hill, NC 27599, USA
[7] University of Washington, Seattle, WA 98195, USA
[8] Duke University, Durham, NC 27708, USA
[9] Armstrong Atlantic State University, Savannah, GA 31419, USA
[10] TRIUMF, Vancouver, BC V6T 2A3, Canada
[11] TU Dresden, D-01062 Dresden, Germany

With assistance this past year from:

- Kurt Nicholson – Guelph U.
- Axel Boeltzig – TU Dresden
- Ben Bellis, Leigh Schaefer, Zander Moss – Duke U.
- Victor Buza, Olivia Zigler – U. Minnesota Duluth
- Brian Redden – Armstrong Atlantic State U
- Thomas Corona – U. North Carolina
- Andre-Philippe Olds – Laurentian U.

Conclusions

- With the addition of large Pb, LAr, and even an Fe detector we would be in much better shape for covering all neutrino flavours
- No one technology covers everything well
- LAr has great potential for providing quality information in ES, CC and NC channels but the level of technical challenge is not clearly well matched to a SN detector
- We should continue to take advantage of opportunities that arrive and advocate for maintaining SN sensitivity in future large-scale detectors.