The HALO-2 Supernova Detector

Vulcano Workshop 2016

FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

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Outline

- Science Motivation
  - Supernovae in general
  - Lead-based detectors in particular
- Supernova Neutrinos
- Lead as a Supernova Neutrino Target
- Event Rates / kt of Lead
- The HALO Detector
- “HALO-2” at LNGS
- Status of HALO-2

Science Motivation
- supernovae in general

- the potential to:
  - learn more about supernova dynamics
  - learn more about properties of neutrinos
  - maximize the science opportunity from the next galactic supernova by promptly alerting the astronomical community (SN Watch / SNEWS)

BUT…

- While the probability of a galactic SN *in a lifetime* are good there are issues:
  - most supernova-sensitive detectors have other primary objectives necessitating down-time; extensive calibration; reconfiguration; and end of life
- While SN emit neutrinos and anti-neutrinos of all flavours in roughly equal numbers, and valuable information is present in all channels,
  - Water Cherenkov and liquid scintillator detectors have dominant $\bar{\nu}_e$ sensitivity
  - future (mega-expensive) detectors can save costs by increasing their energy threshold at the expense of their supernova capabilities – a risk

Science Motivation
- Pb-based detectors in particular

- So, with these issues in mind, it seems there's a niche for a
  - low cost
  - low maintenance
  - robust
  - long lifetime
  - dedicated supernova detector with complementary sensitivity
- Lead, as a supernova neutrino target, has a dominant ν_e sensitivity and some other advantages
- HALO is 79 tonnes of lead instrumented with ^{3}He neutron detectors running since May 2012 at SNOLAB
- HALO-2 is a kilo-tonne concept for LNGS being developed due to the availability of ~1 kilotonne of Pb from the decommissioning of OPERA

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, $\overline{\nu}_e$, ν_x luminosities reflecting aspects of SN dynamics
  - Presence of neutronization pulse
  - Hardening of spectra through accretion phase then cooling

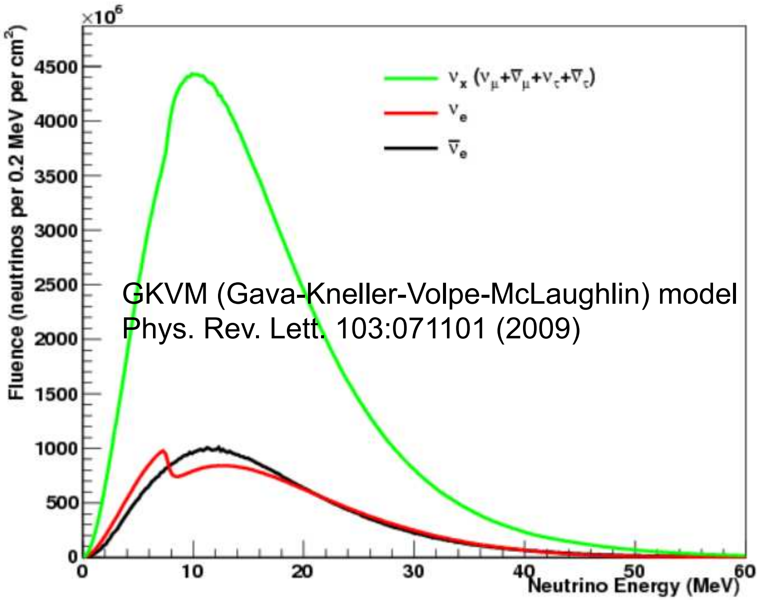
- Fermi-Dirac thermal energy distributions characterized by a temperature, T_ν, and pinching parameter, η_ν

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

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

$$T(\nu_x) > T(\overline{\nu}_e) > T(\nu_e)$$

- ν-ν scattering collective effects and MSW oscillations further imprint physics on the F-D distributions



K. Scholberg, Annu. Rev. Nucl. Part. Sci. 2012. 62:81–103.

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
  - Presence of axions, exotic physics, or extra large dimensions (cooling rate)
  - Etc.

Lead as a Supernova Neutrino Target

- CC and NC cross-sections are the largest of any reasonable material though thresholds are high
- Neutron excess (N > Z) Pauli blocks

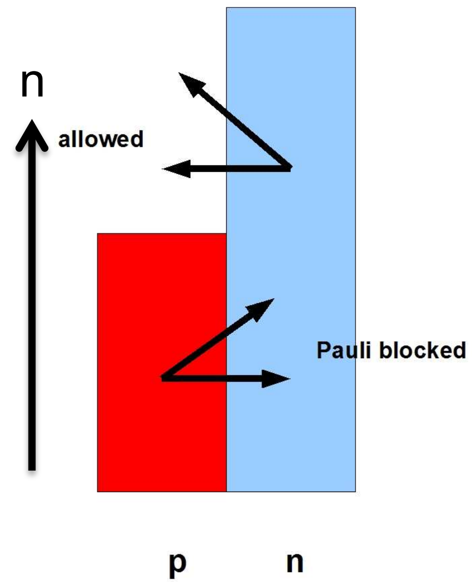
$$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$$

- High Z increases ν_e CC cross-sections relative to $\overline{\nu}_e$ CC and NC due to Coulomb enhancement further suppressing the $\overline{\nu}_e$ CC channel
- Results in mainly ν_e sensitivity - complementary to water Cerenkov and liquid scintillator detectors
- de-excitation of nucleus following CC or NC interactions is by 1n or 2n emission

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

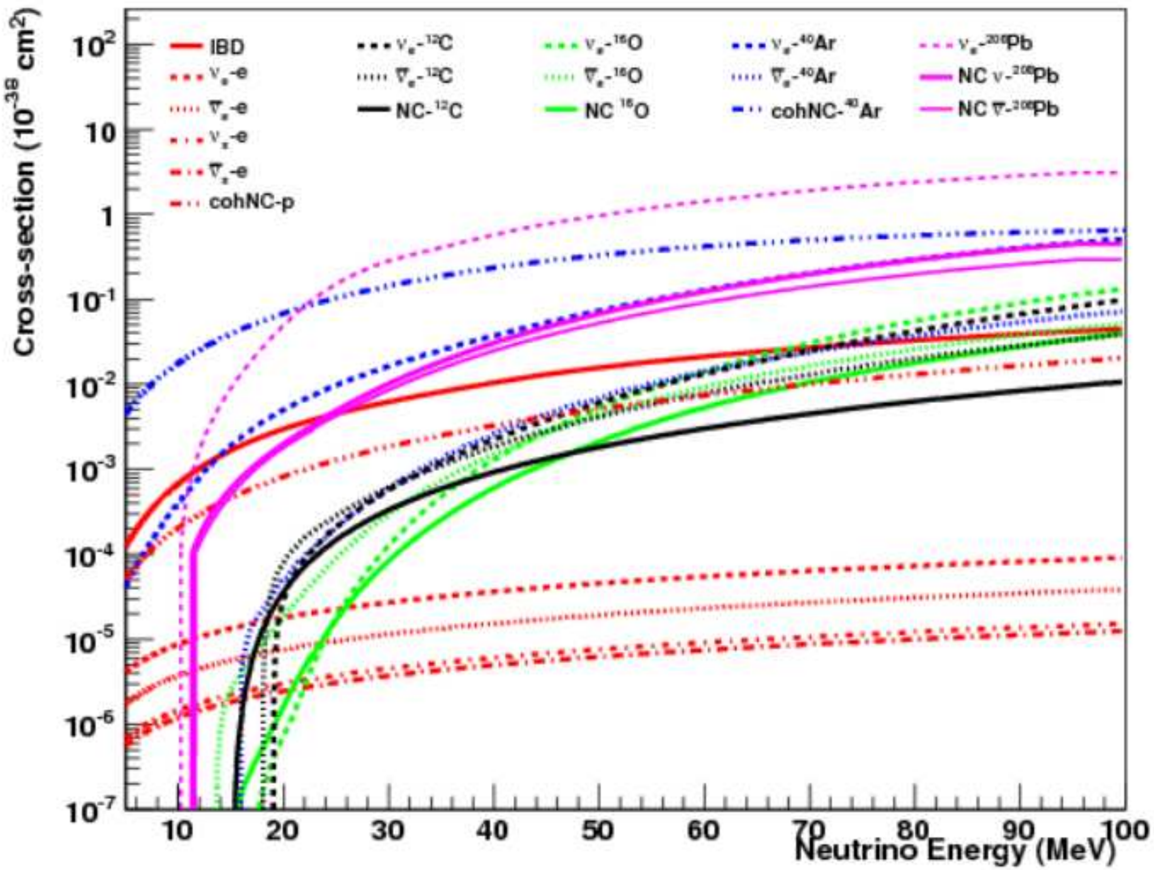
  for moderating neutrons down to epithermal energies



Limitations

- no directionality
- no direct measure of neutrino energy

Comparative ν-nuclear Cross-sections



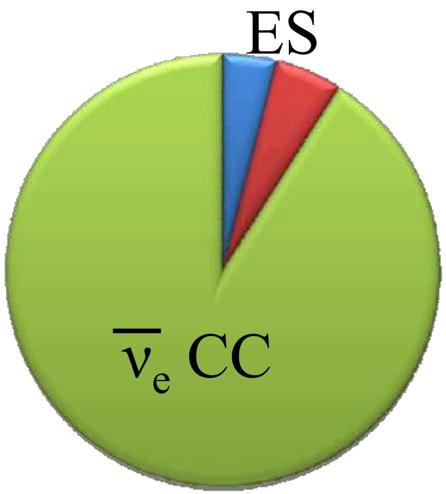
K. Scholberg, Annu. Rev. Nucl. Part. Sci. 2012. 62:81–103.

$$
\begin{aligned}
\text{CC:}\quad \nu_e + {}^{208}\text{Pb} &\rightarrow {}^{207}\text{Bi} + n + e^- \\
\nu_e + {}^{208}\text{Pb} &\rightarrow {}^{206}\text{Bi} + 2n + e^- \\
\text{NC:}\quad \nu_x + {}^{208}\text{Pb} &\rightarrow {}^{207}\text{Pb} + n \\
\nu_x + {}^{208}\text{Pb} &\rightarrow {}^{206}\text{Pb} + 2n
\end{aligned}
$$

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

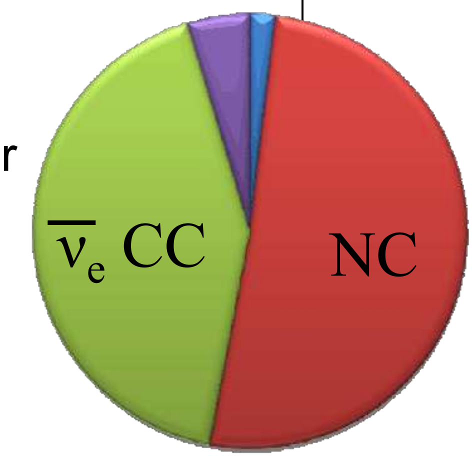
2n cross-sections don't appear on plot but provide a handle on energy distribution

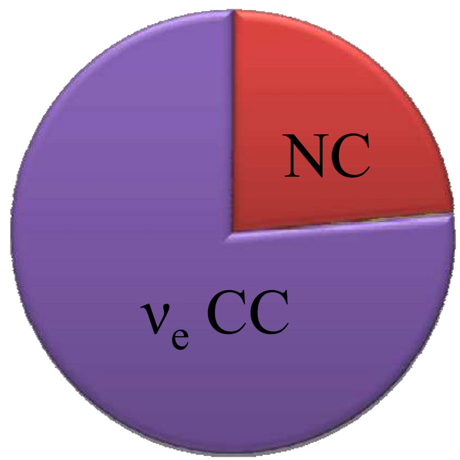
Flavour Sensitivities for Different Technologies



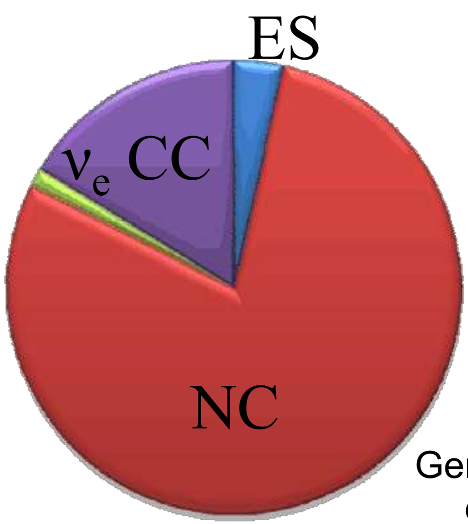
Water Cherenkov

Liquid Scintillator



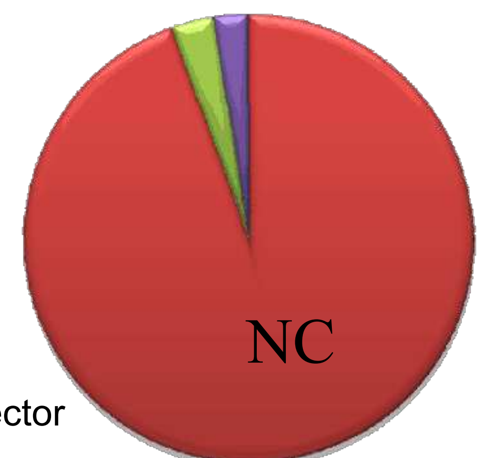


Lead



Liquid Argon

Iron



Generally functions of neutrino temperatures and detector energy thresholds, also needs updating for large θ_{13}

Event Rates / kt of Lead (100% capture efficiency)

$\langle E^0_{\nu_x} \rangle$ [MeV]	13	18				25
MH (and θ_{13})	NMH small θ_{13}	IMH		NMH small θ_{13}		IMH
α_{ν_x}	7	2	7	2	7	2
N_{1n}	90	390	285	300	225	570
N_{2n}	< 3	150	30	105	24	390
neutrons emitted	~ 90	690	345	510	273	1350

Table 6. Total numbers of events during the explosion (assuming 100 % detection efficiency, distance to the supernova 10 kpc and target mass 1 kton of ^{208}Pb). As in table 4 but assuming equal neutrino luminosities throughout the whole neutrino emission and the total time integrated luminosity 3×10^{53} erg.

from Väänänen and Volpe, JCAP **1110** (2011) 019.

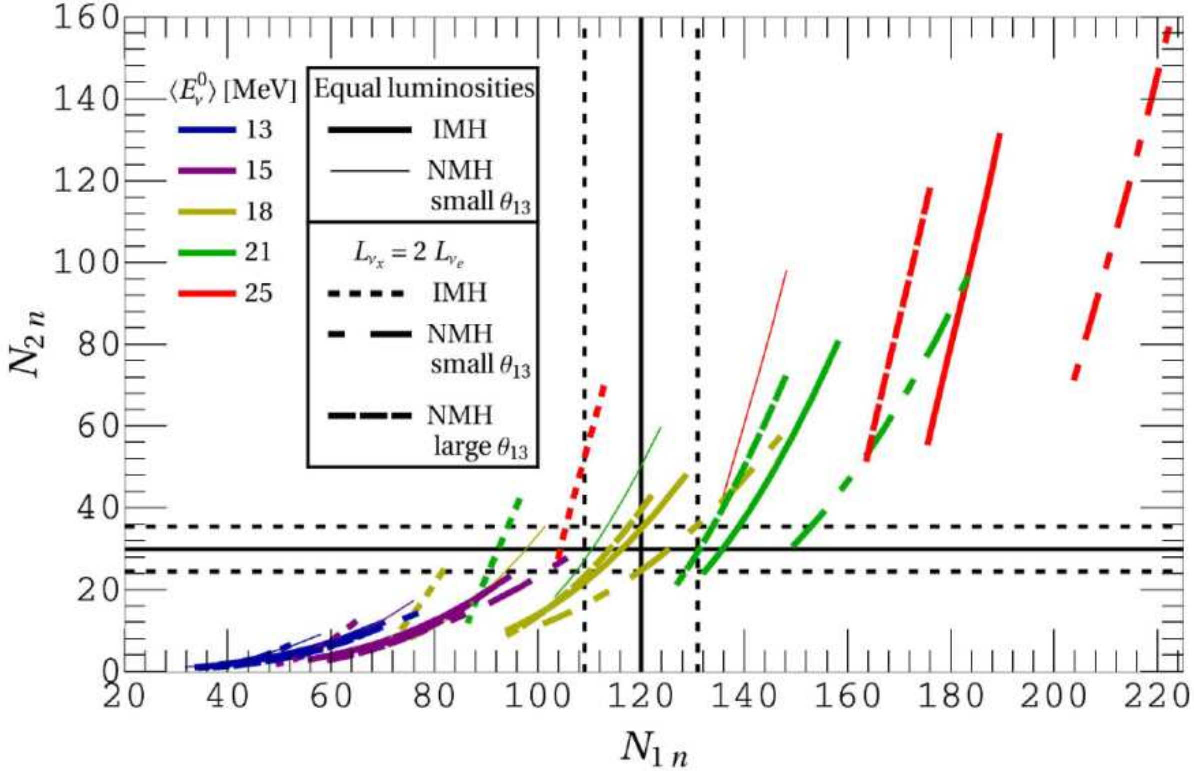
Earlier work, in 1kt of lead for a SN @ 10kpc†,

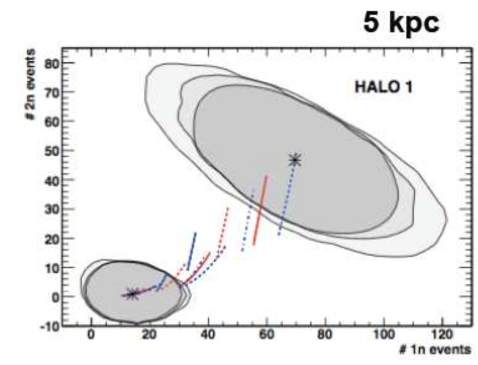
- Assuming FD distribution with T=8 MeV for ν_x.
- 860 neutrons through ν_e charged current channels
  - 380 single neutrons
  - 240 double neutrons (480 total)
- 250 neutrons through ν_x neutral current channels
  - 100 single neutrons
  - 75 double neutrons (150 total)

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

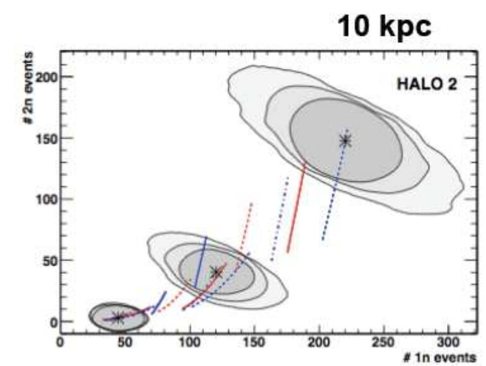
(more conservative neutrino temperatures reduce these event numbers by a factor of ~2)

Sensitivity to neutrino energy





ε = 40%,50%,60%



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 Väänänen and Volpe, JCAP **1110** (2011) 019

March 2012 APS, K. Scholberg.

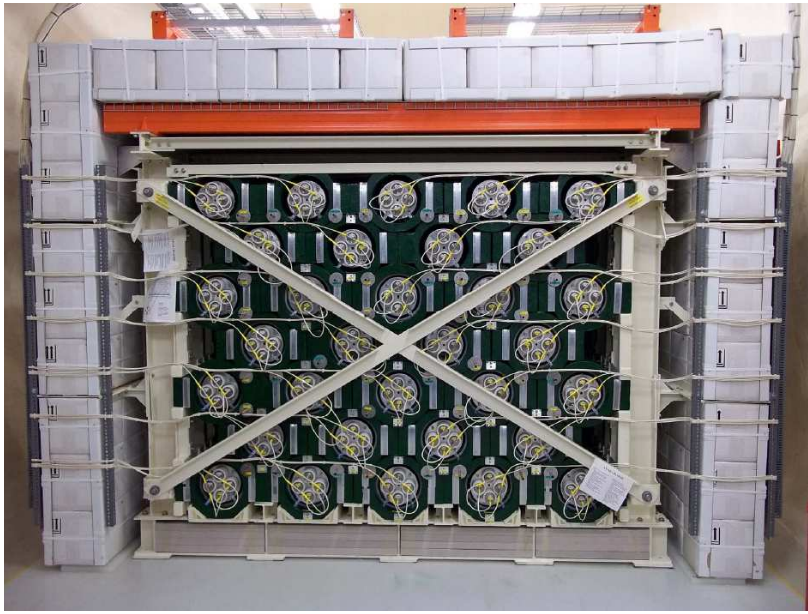
HALO - a Helium and Lead Observatory

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

+

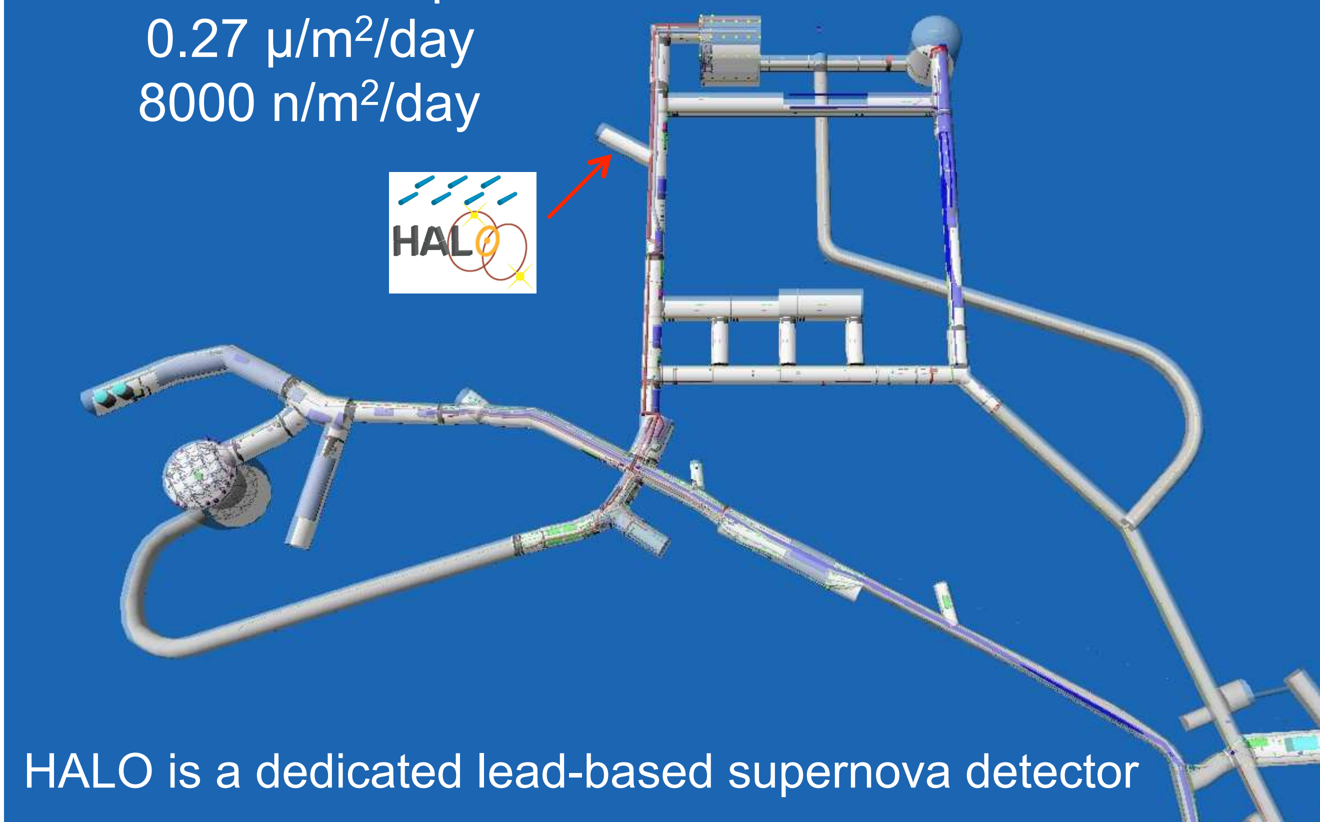
"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



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

HALO at SNOLAB

SNOLAB 6800’ campus
6000 mwe depth
0.27 μ/m²/day
8000 n/m²/day



HALO is a dedicated lead-based supernova detector

The HALO Collaboration

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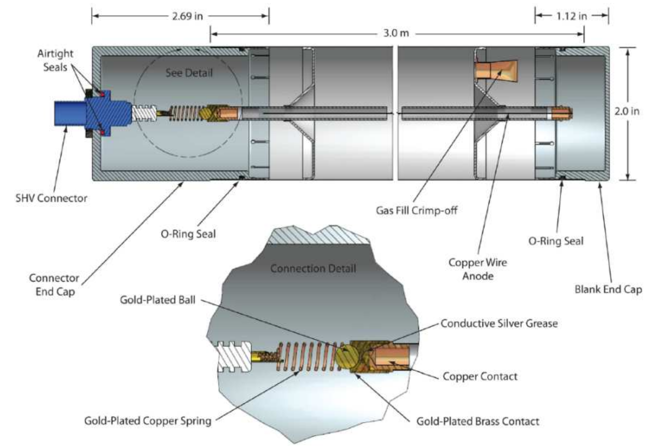
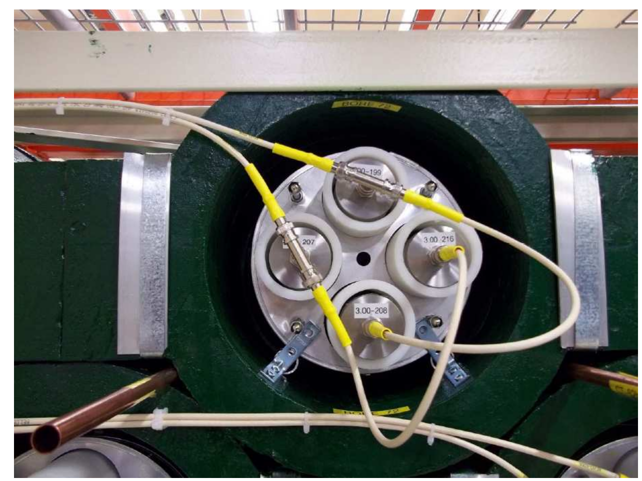
Funded by:

halo.snolab.ca

Neutron detection in HALO

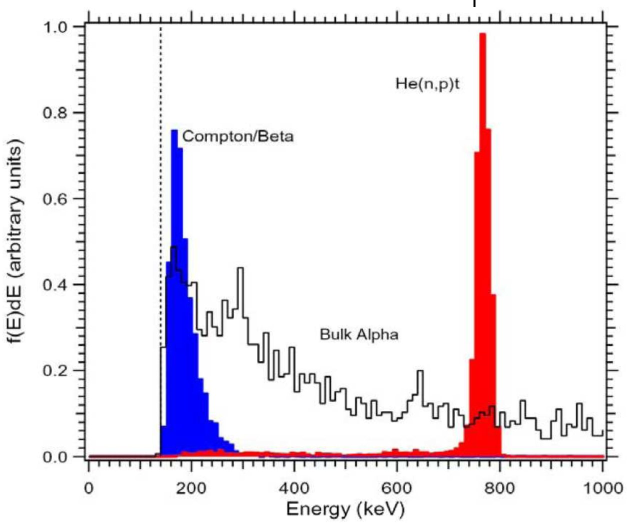
- Re-using SNO's "NCD" ^{3}He proportional counters
- 5 cm diameter x 3m and 2.5m in length, ultra-pure CVD Ni tube (600 micron wall thickness)
- 2.5 atm (85% ^{3}He, 15% CF_4, by pressure)
- Four detectors with HDPE moderator tubes in each of 32 columns of lead rings
- 128 counters (~370 m) paired for 64 channels of readout
- an additional ~200m of ^{3}He proportional counters are also available

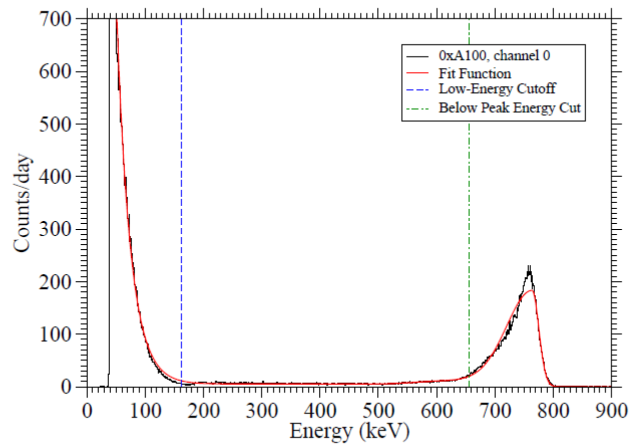




Neutron detection in HALO

- Neutron detection via
  $^{3}He + n \rightarrow p + t + 764$ keV
- 764 keV FE peak plus LE tail due to wall effects
- measured neutron capture efficiency ~30% volume averaged; 47% central **new**
- α's present at rate of ~20 events per day in ROI for the entire array
- Compton and beta events at low energies
- 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 / detector but running at threshold of ~50 keV for total rate of 5 Hz
- Current neutron rate in HALO is 0.015 Hz (~1300 / day)





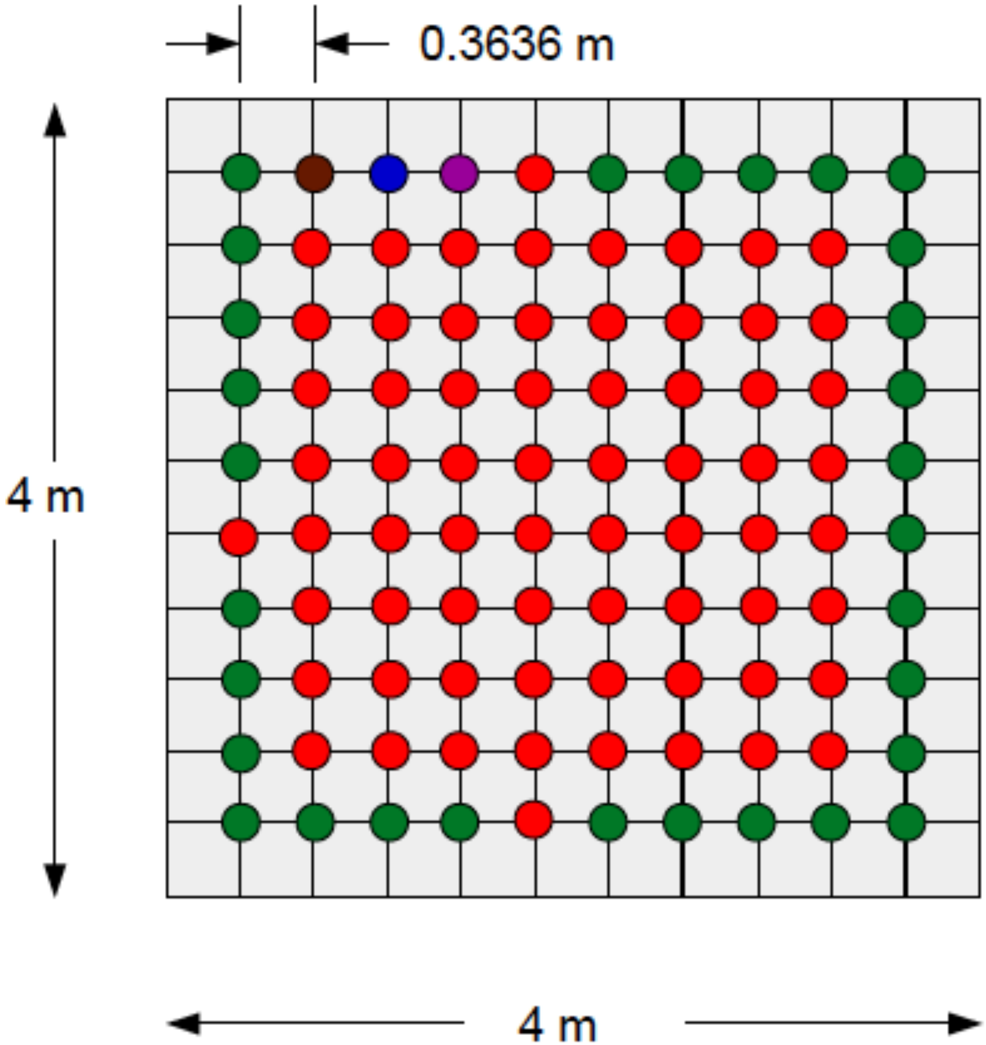
Status today

- Full detector being read-out since May 8th 2012.
- 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
- work continues on redundant systems and monitoring tools

"HALO-2" at LNGS

- the decommissioning of OPERA has made available ~ 1 kilotonne of Pb for new ideas
- concepts for HALO-2 are preliminary
  - have ~500 m of ^{3}He counters (very quiet)
  - plus 120 m of $^{10}BF_3$ counters
  - likely more is desirable and/or an alternative technology (could be less quiet if not used in trigger)
  - cosmic muon rate ~x100 higher in LNGS
    - veto might be desirable, not absolutely necessary
  - modest (water) shielding should reduce ambient neutrons to negligible level, as well as isolate and define the target volume

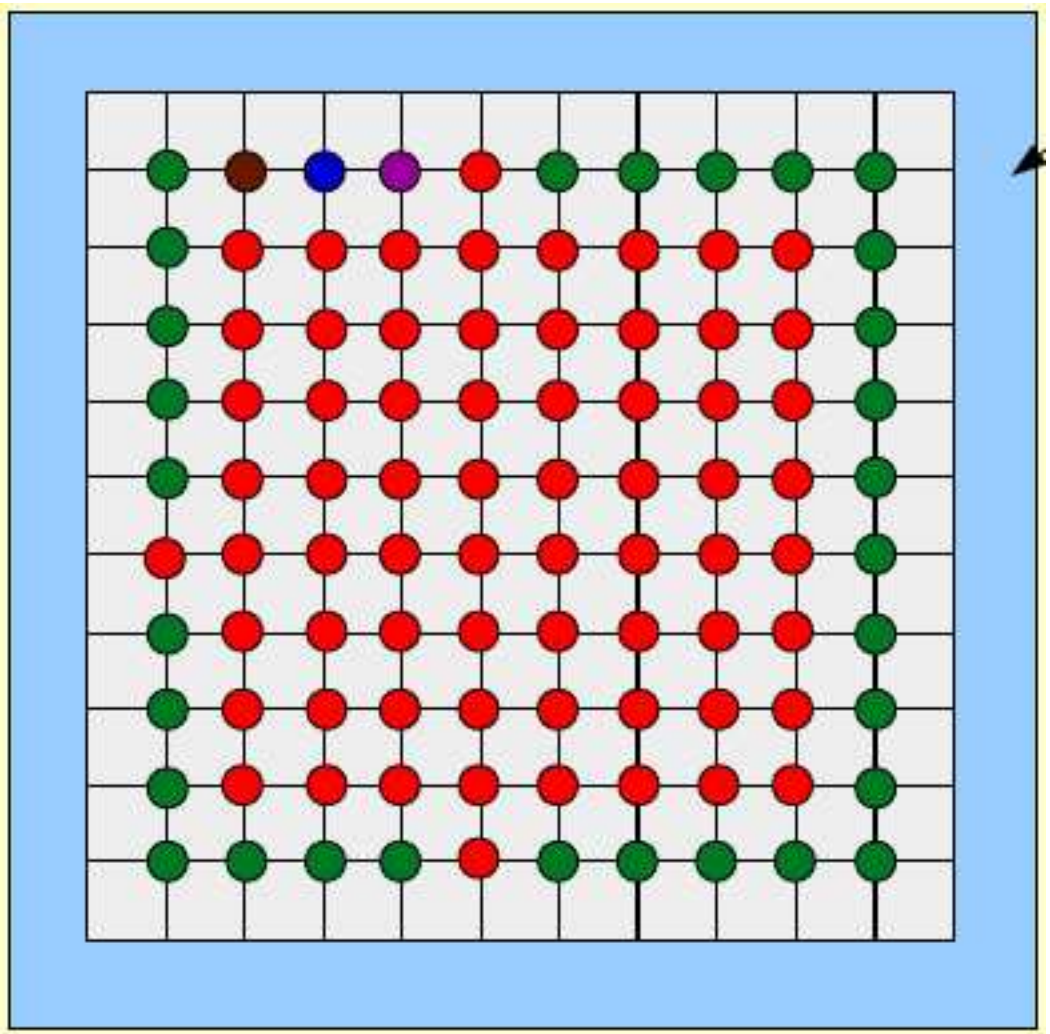
"HALO-2" at LNGS



Starting Point

- distribute all available ^{3}He detectors in a 4m x 4m x 5.5m volume of Pb
- simulate MeV neutrons in Pb
- find 1/4 capture on ^{3}He; 1/3+ capture on Pb; 1/3+ escape volume
- recall neutron capture efficiency in HALO is ~30%; so gain factor of 12 in Pb mass; lose some efficiency

"HALO-2" at LNGS



Next…. add water layer as reflector

- for HALO (smaller volume; larger surface/ volume ratio) this had significant benefits
- for HALO-2 capture on Pb increases; detection on 3He ~unchanged
- needed as part of the design, in any case, to isolate from environmental neutrons and to define target volume

"HALO-2" at LNGS

- not satisfied with 25% neutron capture efficiency… HALO achieved 47% in central volume so with more favourable surface/volume ratio HALO-2 should do better
- increasing density of neutron detection will increase capture efficiency / scientific reach of detector AND costs
- more ^3He detectors not feasible with greatly increased cost of 3He; looking towards BF_3 and Gd-clad plastic scintillator
- exploration with detailed simulations in progress
- backgrounds in ^3He counters are lower than required for setting a low threshold SN trigger → likely design feature would be a central volume of detector instrumented with ^3He and surrounding volume with alternative technology… to be explored

"HALO-2" at LNGS

Insights from MC studies

- scaling with detector densities and gas pressures not quite intuitive
- choice of moderator (plastic, graphite, water, heavy water) has only weak effects on capture efficiency
- geometry matters – moderating close to neutron detectors is better and allows an increase in capture efficiency over the naïve mole.barn fraction of the detectors
- fraction of neutrons escaping Pb volume is important and not greatly affected by the geometrical details interior to the volume
- finding a way to detect the escaping neutrons is likely the largest win in detection efficiency; additional detectors an expensive option; studying Gd layer and gamma catcher options

HALO-2 Status

- still in the “fun” conceptual stage – ~unconstrained but conscious that increasing costs diminish likelihood of realization
- expressed an interest in the OPERA lead to the LNGS Scientific Committee in April 2015
- have formed a working group with bi-weekly meetings to discuss simulations
  - 6 HALO members
  - 9 new Italians
  - 4 new Canadians
  - 4 new Americans
- made a submission to the LNGS “10 year Plan for UG Resources” exercise in February 2016
- planning to grow and transition working group to a collaboration and produce an LOI and technical design study on a 1 year timescale

Interested?

To help in the development of the LOI and TDS please contact

Clarence Virtue

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Thanks for your attention!