A Future Lead-based Supernova Detector at LNGS

LNGS future, 2020 and beyond

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A Perceived Opportunity…

Two elements:

- The availability of ~1kt of OPERA lead for new experiments
- HALO at SNOLAB, an operating lead-based supernova detector with 80 tonnes of lead

motivate us to fully explore the possibility of combining resources to create a significantly more capable lead-based supernova detector at LNGS

Outline

- Science Motivation
- Lead as a Supernova Neutrino Target
- Event Rates / kt of Lead
- The HALO Detector
- “HALO” at LNGS
- Technical Challenges and Risks
- Costs and Space Requirements
- Infrastructure Requests
- Safety Issues and Timescales

Science Motivation

- While the probability of a galactic SN in a lifetime are good, most supernova-sensitive detectors have other primary objectives necessitating down-time; extensive calibration; reconfiguration; and end of life
- 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
- Water Cherenkov and liquid scintillator detectors have dominant $\bar{\nu}_e$ sensitivity but, valuable information is present in other channels too
- Lead will provide a dominant ν_e sensitivity

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

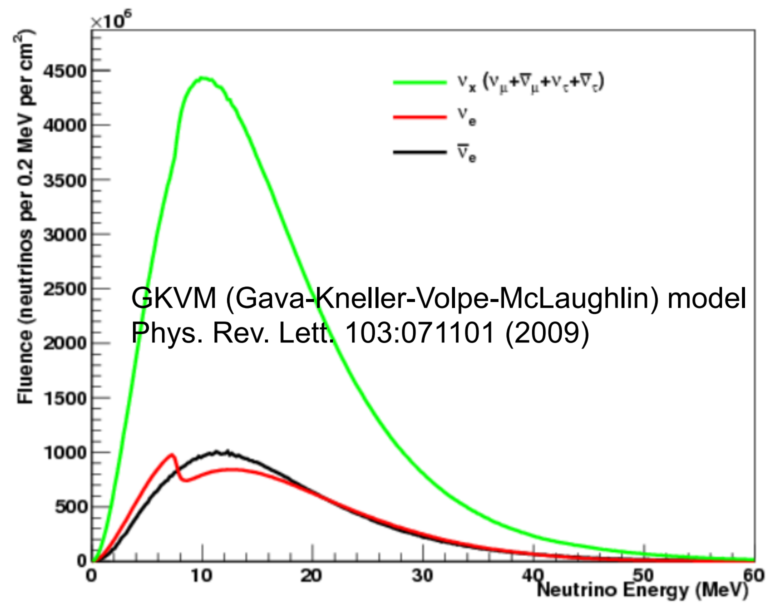
- Fermi-Dirac thermal energy distributions characterized by a temperature, T_ν, and pinching parameter, η_ν

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

- 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 FD distributions



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

What is to be Learned?

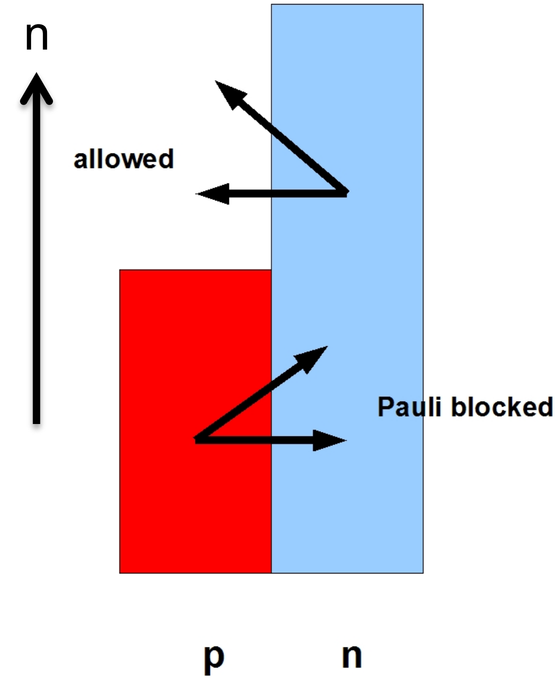
- Astrophysics
  - Explosion mechanism
  - Accretion process
  - Black hole formation (cutoff)
  - Presence of Spherical accretion shock instabilities (3D effect)
  - Proto-neutron star EOS
  - Microphysics and neutrino transport (neutrino temperatures and pinch parameters)
  - Nucleosynthesis of heavy 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

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

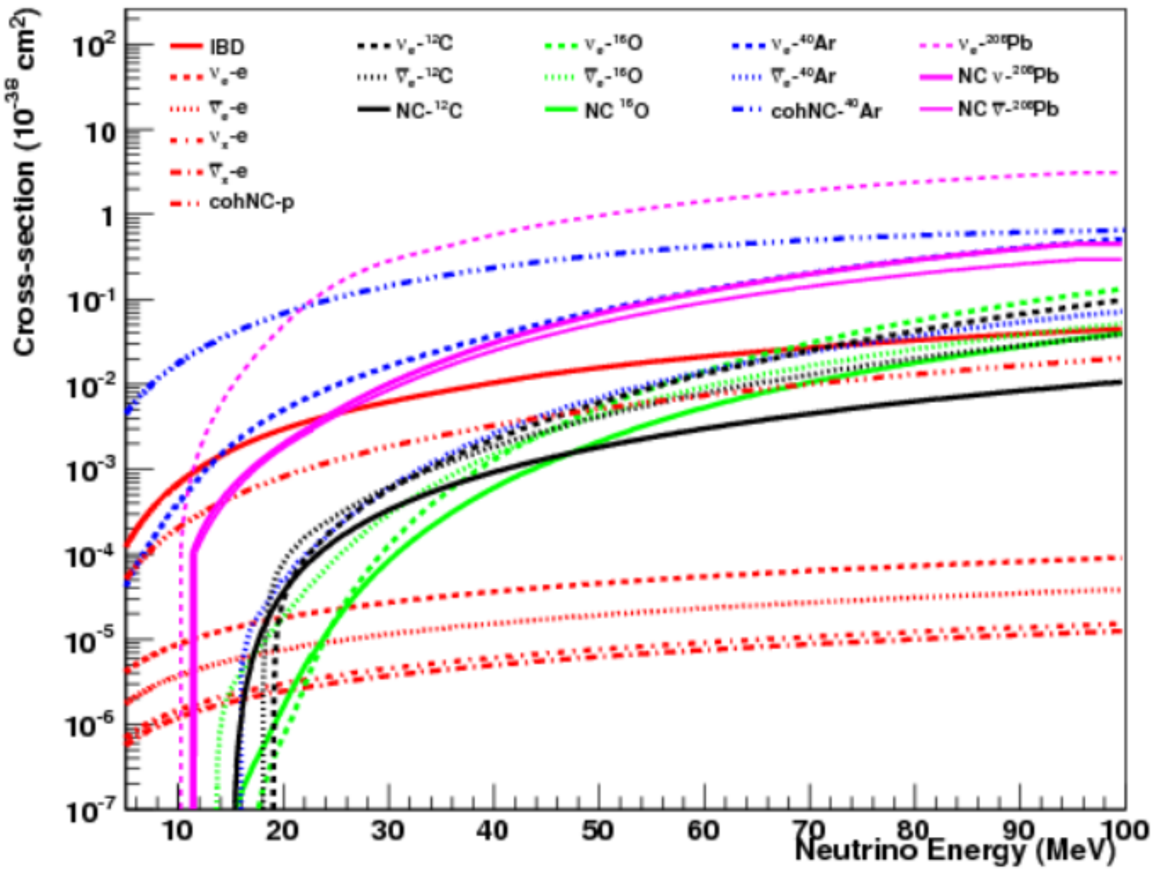
- High Z increases ν_e CC cross-sections relative to $\overline{\nu}_e$ CC and NC due to Coulomb enhancement further suppressing the $\overline{\nu}_e$ CC channel
- Results in mainly ν_e sensitivity - complementary to water Cerenkov and liquid scintillator detectors
- de-excitation of nucleus following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

Comparative ν-nuclear Cross-sections



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

CC:

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$$
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$

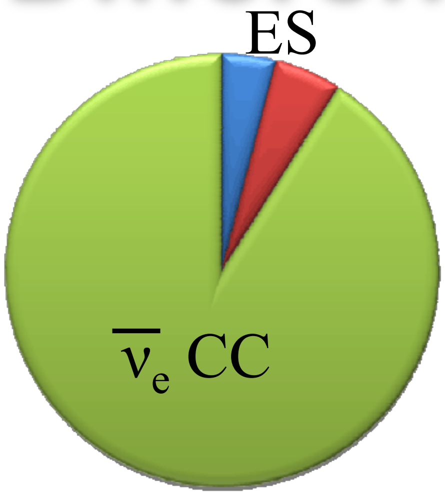
NC:

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

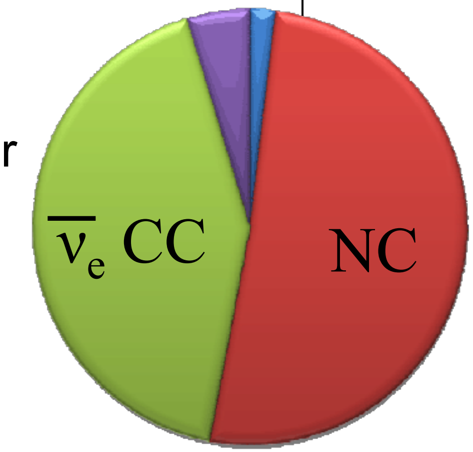
Thresholds
CC 1n 10.7 MeV
CC 2n 18.6 MeV
NC 1n 7.4 MeV
NC 2n 14.4 MeV

2n cross-sections don't appear on plot

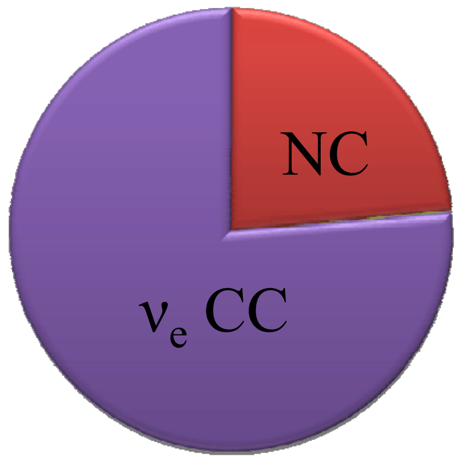
Flavour Sensitivities for Different Technologies



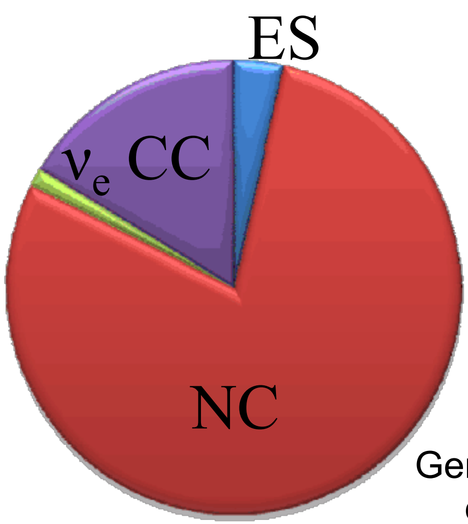
Water Cherenkov



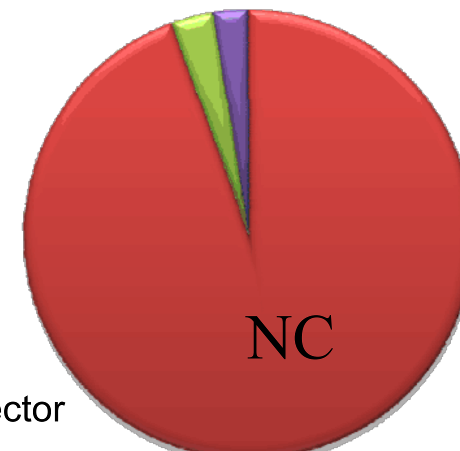
Liquid Scintillator



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

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

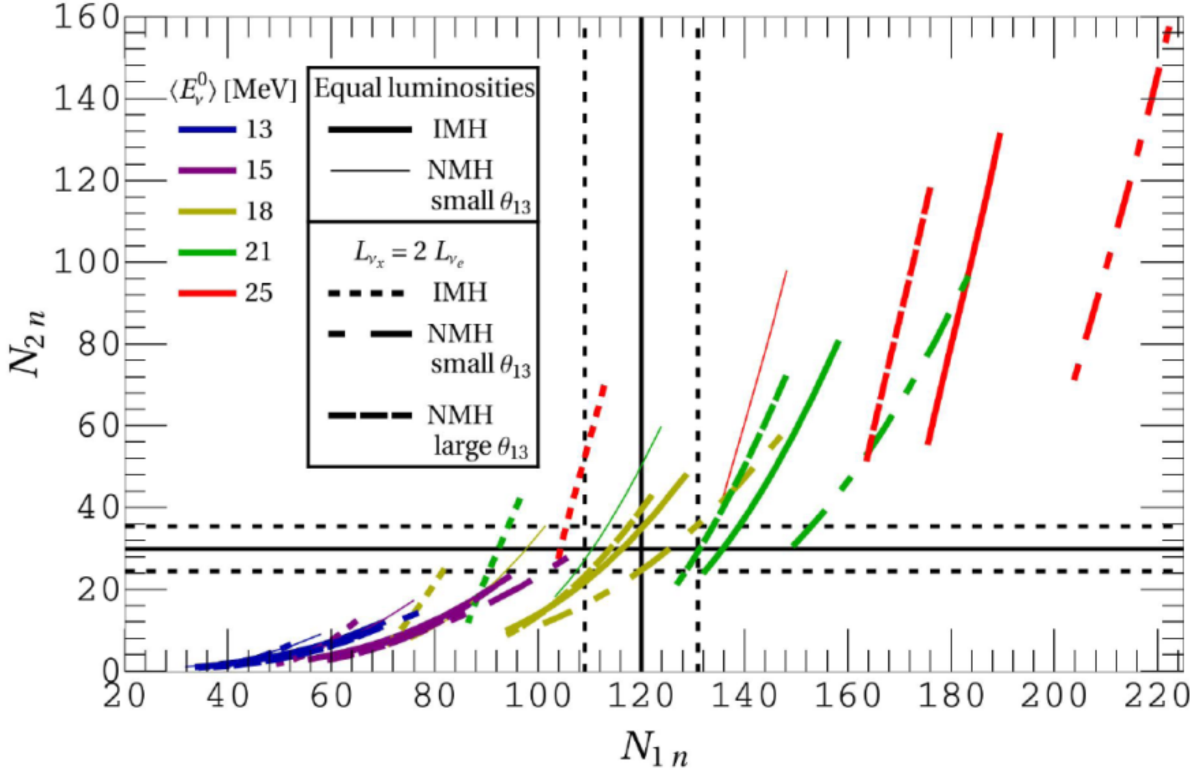
Table 6. Total numbers of events during the explosion (assuming 100 % detection efficiency, distance to the supernova 10 kpc and target mass 1 kton of ^{208}Pb). As in table 4 but assuming equal neutrino luminosities throughout the whole neutrino emission and the total time integrated luminosity 3×10^{53}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

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

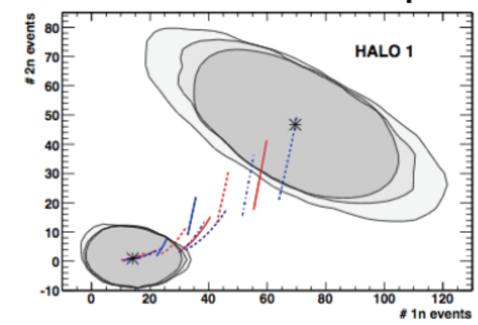
- Assuming FD distribution with T=8 MeV for ν_x.
- 860 neutrons through ν_e charged current channels
  - 380 single neutrons
  - 240 double neutrons (480 total)
- 250 neutrons through ν_x neutral current channels
  - 100 single neutrons
  - 75 double neutrons (150 total)

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

Sensitivity to neutrino energy

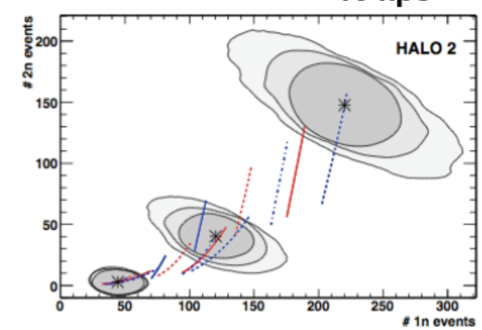


5 kpc



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

March 2012 APS, K. Scholberg.

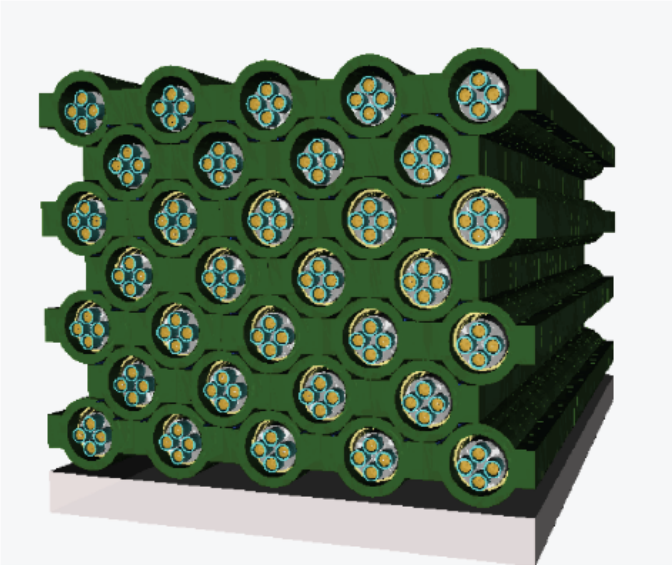
HALO - a Helium and Lead Observatory

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

+

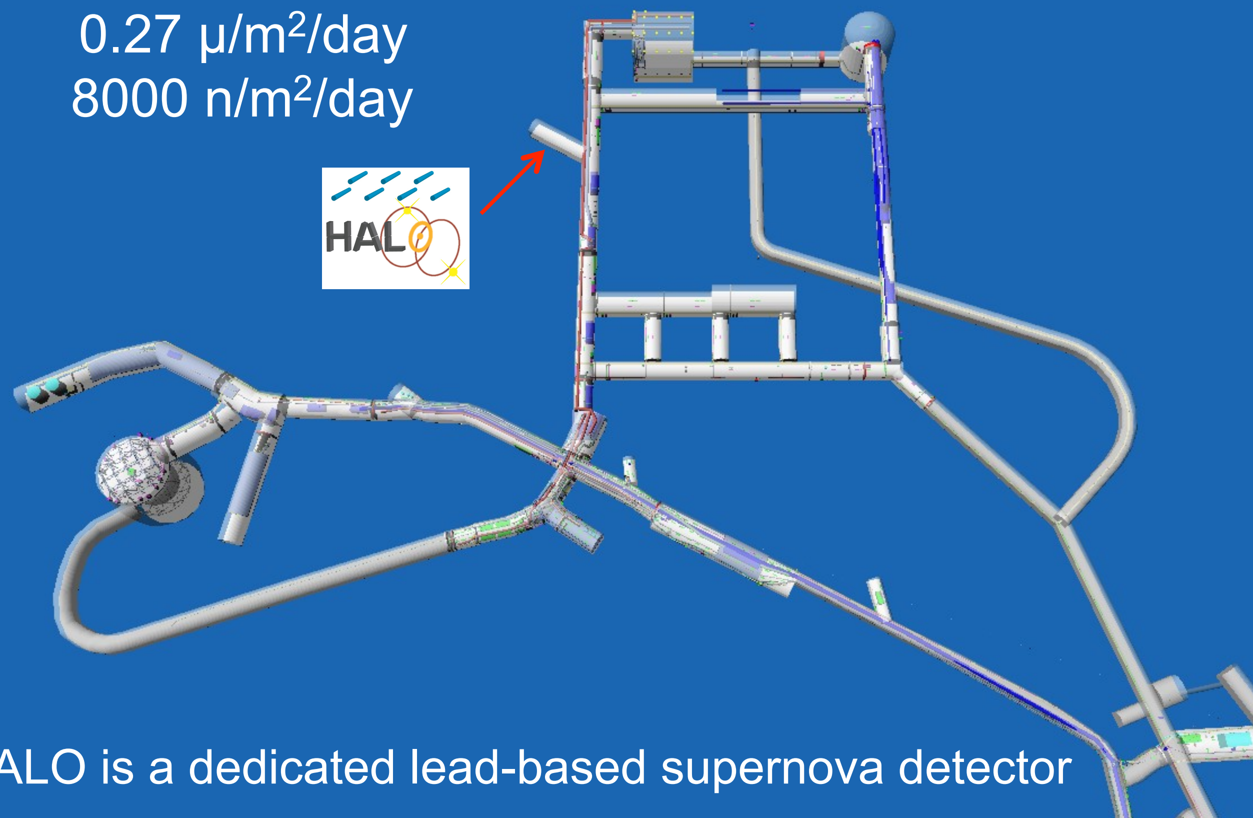
"Lead" – because of high [illegible]-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



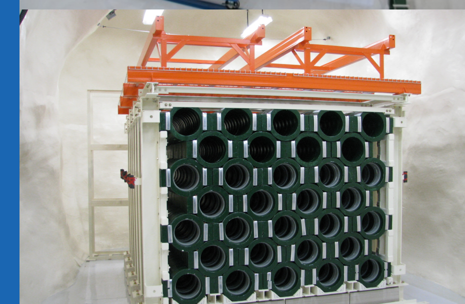
HALO is using lead blocks from a decommissioned cosmic ray monitoring station

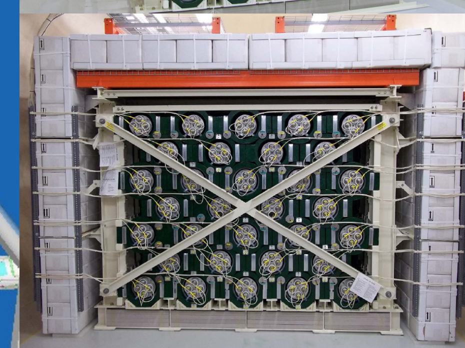
HALO at SNOLAB

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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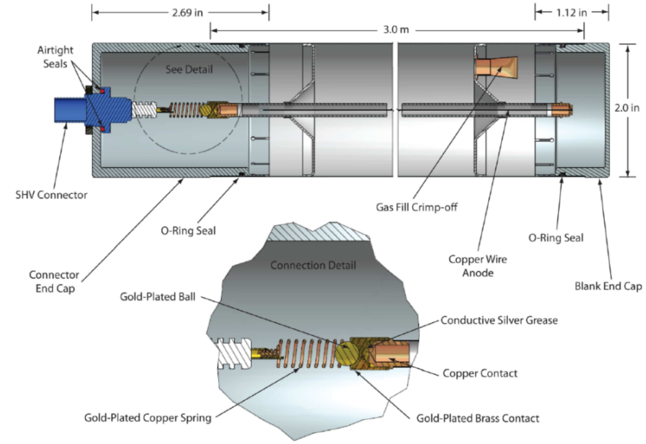
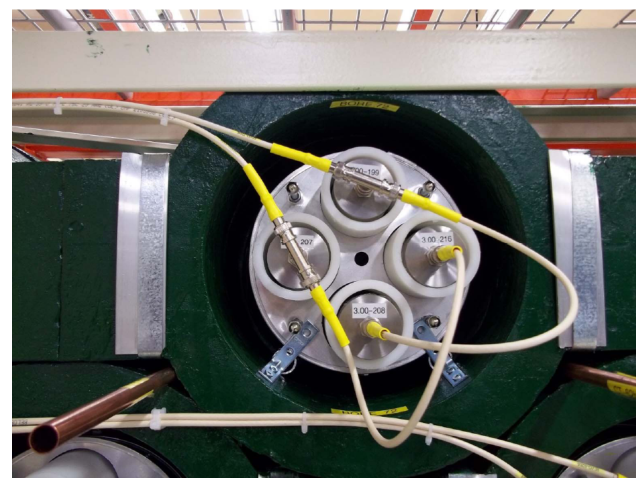
Funded by: NSERC CRSNG, NSF

halo.snolab.ca

Neutron detection in HALO

- Re-using SNO's "NCD" ^3He 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% ^3He, 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 ^3He proportional counters are also available



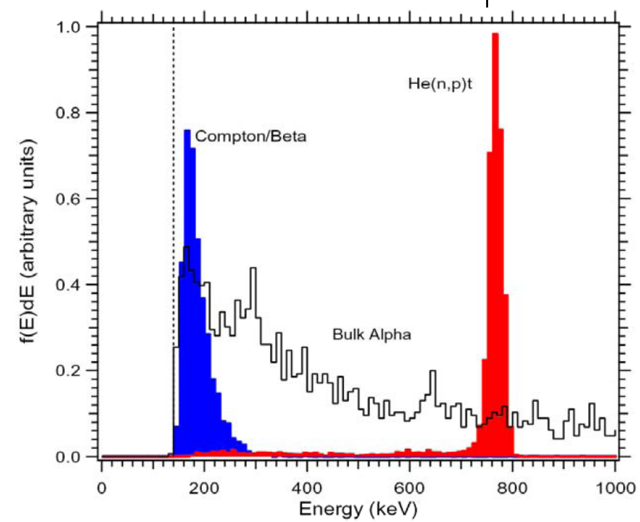


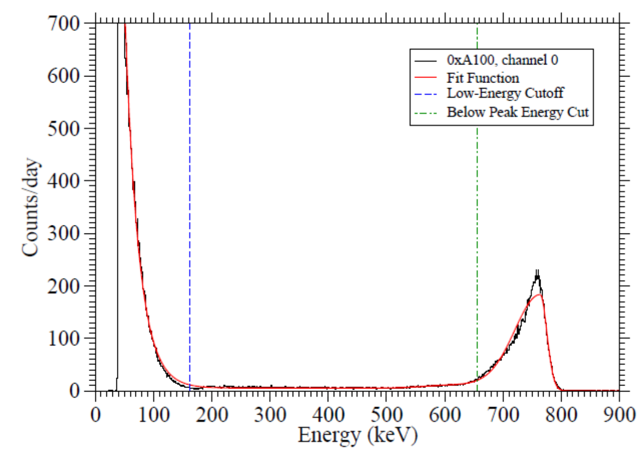
Neutron detection in HALO

- Neutron detection via

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

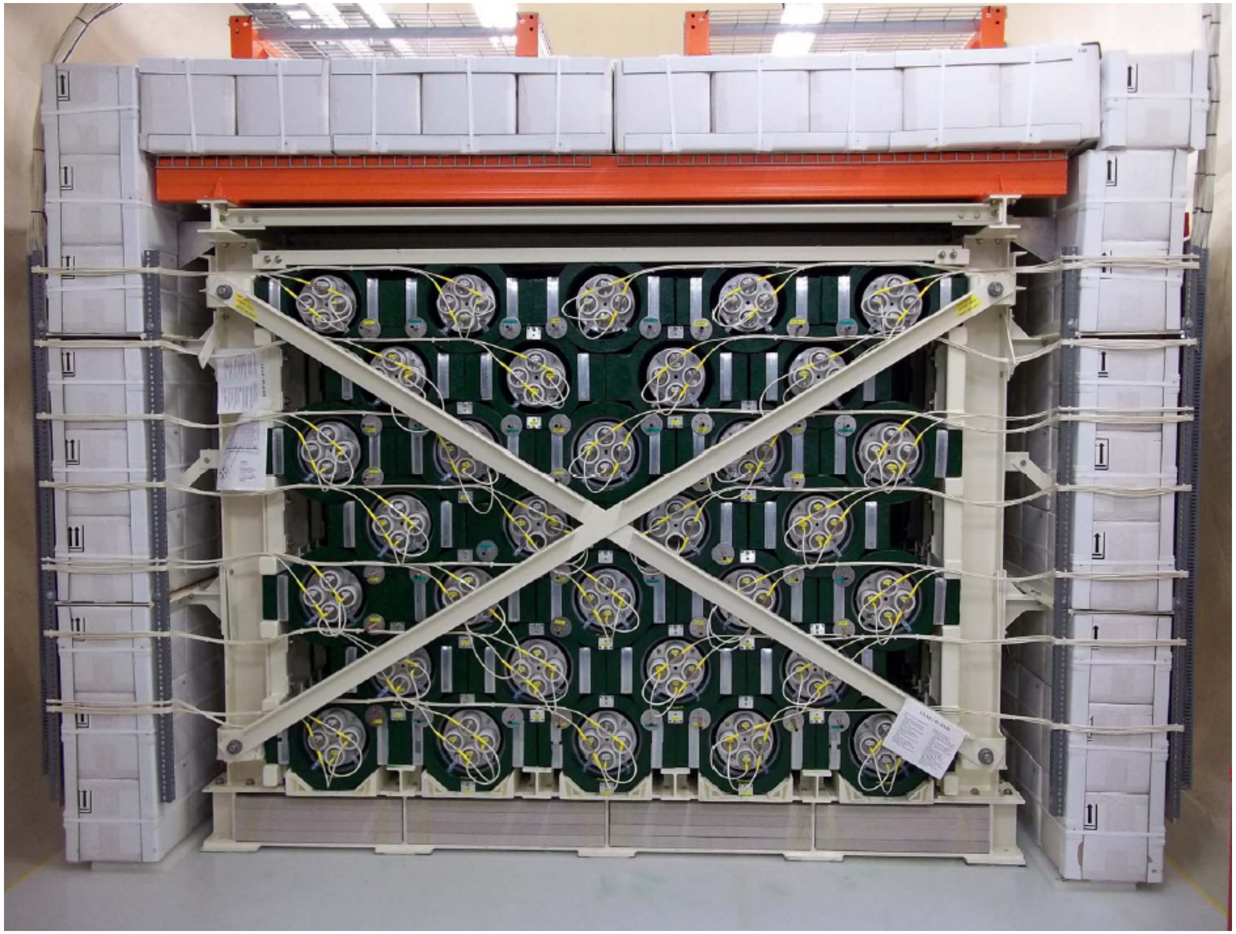
- 764 keV FE peak plus LE tail due to wall effects
- α's present at rate of ~20 events per day for the entire array
- Compton and beta events at low energies
- Background n in room at level of 4000 fast plus 4000 thermal per m^2 per day.
- Cosmic muons < 2 per day
- Intrinsic tritium rate (18.6 keV endpoint) above 12 keV threshold ~10 Hz but running at threshold of ~25 keV for total rate of 4 Hz with partial shielding
- Current neutron rate in HALO with incomplete shielding ~0.1 Hz





Status today

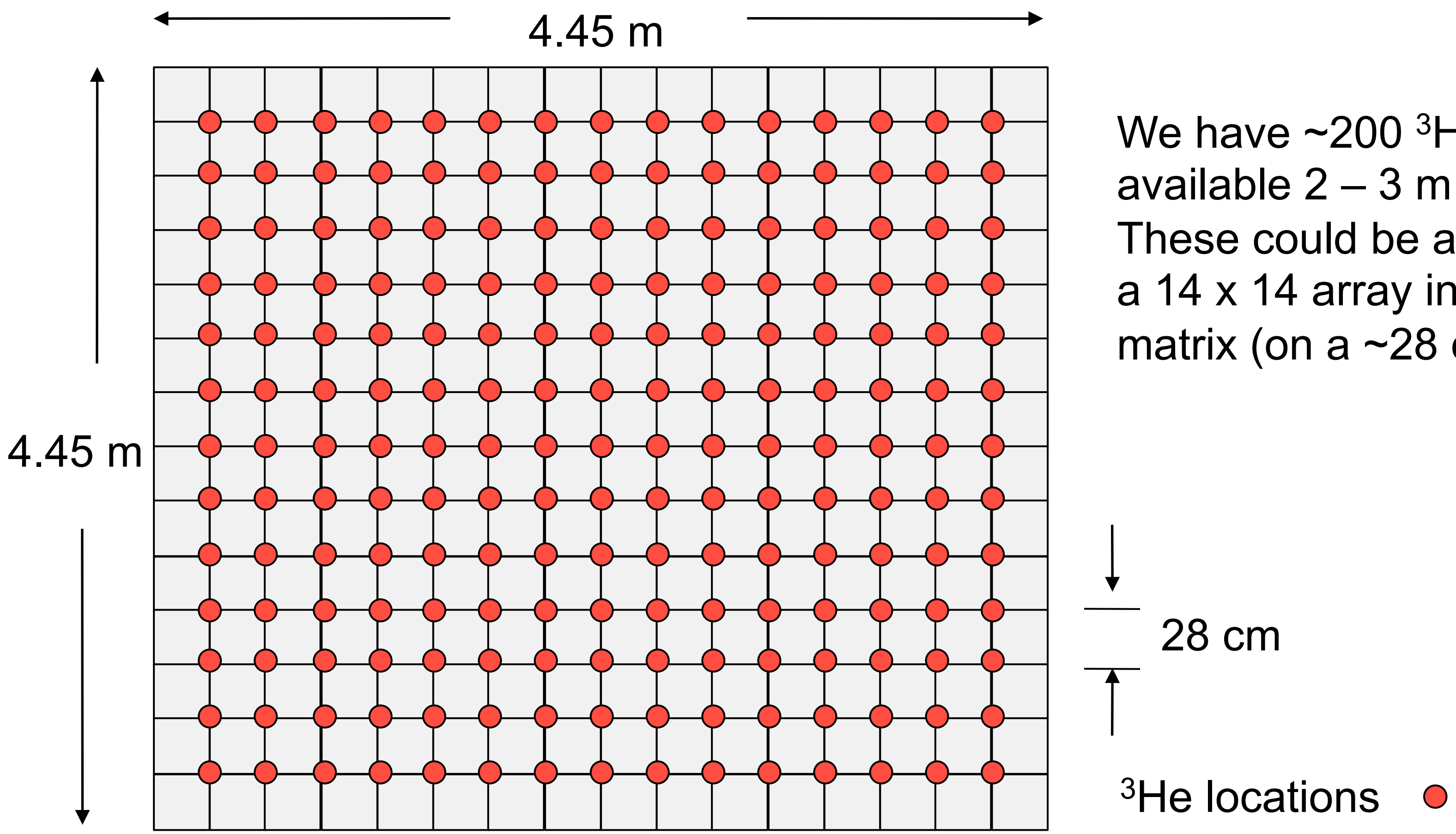
- HV on all channels and full detector being read-out since May 8th 2012.
- Daily shift-taking since July 27th 2012.
- Event GPS timestamping implemented
- Remote control, monitoring and alarm capability being finalized
- Final Calibration proceeding before shielding completion
- Burst trigger being tested with SNEWS



“HALO” at LNGS

- concepts are preliminary
  - have ~600 m of ^3He counters (very quiet… ~40 /day)
  - 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 desirable, not absolutely necessary
  - modest (water) shielding should reduce ambient neutrons to negligible level, isolate and define the target volume

“HALO” at LNGS



We have ~200 ^{3}He counters available 2 – 3 m long. These could be arranged in a 14 x 14 array in the lead matrix (on a ~28 cm grid)

“HALO” at LNGS

- increasing density of neutron detection will increase capture efficiency / scientific reach of detector AND costs
- needs full exploration with detailed simulations
- backgrounds in ^{3}He counters are lower than required for setting a low threshold SN trigger → central volume of detector instrumented with these and surrounding volume with alternative technology… to be explored

Technical Challenges

Technical challenges

- optimizing neutron capture efficiency
  - control of neutron absorbing and moderating materials in the target volume while meeting general engineering and seismic requirements
  - creep an issue with pure lead; PbCa alloy?
  - identifying additional cost-effective neutron detection
- CC sensitivity?
  - if achievable, a significant enhancement

Technical Risks

- transport of the ^3He detectors
  - have rough concepts… to be engineered
  - would evaluate in engineering runs with instrumented shipping container
- aging / lifetime of ^3He detectors
  - can be evaluated in running HALO detector

Costs

- modest on the scale of many projects
  - reforming lead
  - structural support for lead
  - increased readout
  - muon veto, shielding, reflector?
  - additional neutron detection

Space Requirements

- detector is potentially quite compact, as small as 5m x 5 m x 5 m, depending on:
  - need for neutron shielding
  - need for muon veto system
- even then ~50 m^2 floor space may be adequate; more required during construction

Requests for technical and technological infrastructures

- local assistance with structural engineering aspects makes sense
- any reforming of the INFN lead would also be done in Italy (led by local collaborators?)
- otherwise potentially a small impact

Safety Issues and Timescales

Safety issues

- lead handling
- BF_3 hazards if used

Time scale for proposal

- could proceed on a shorter timescale than “2020”
- LOI for Fall 2015?
- Proposal Fall 2017?

Interested?

To help in the development of the LOI and Full Proposal please contact

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