HALO and HALO-1kT

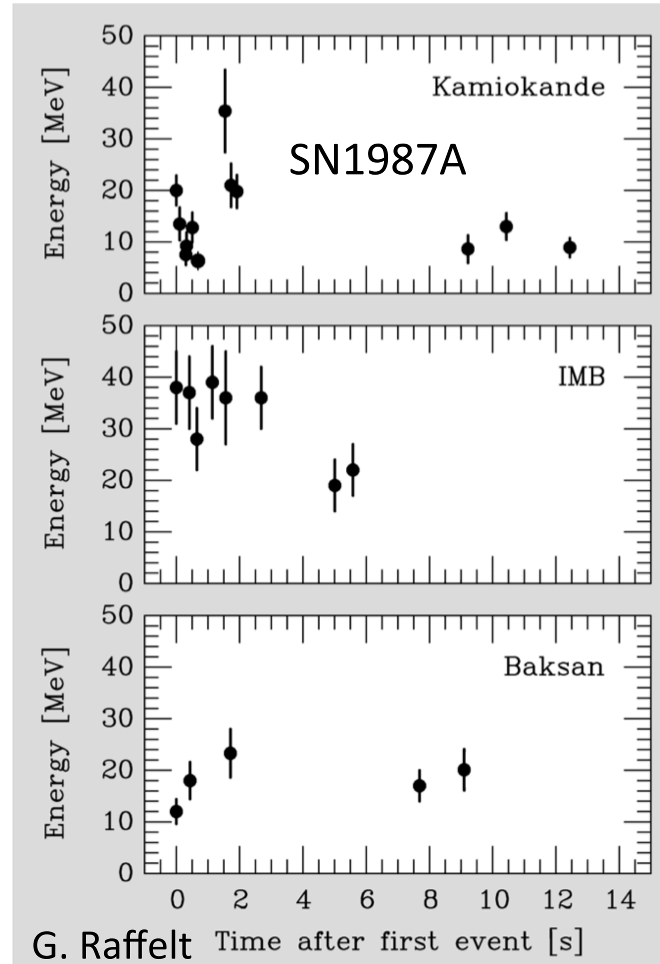
C.J. Virtue for the Collaboration

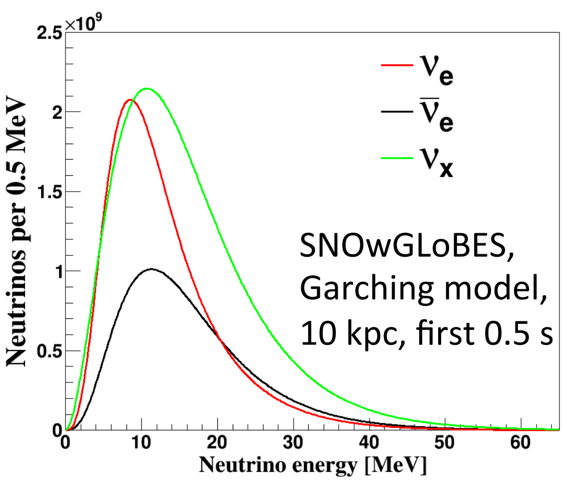
Outline

- Supernova Neutrinos
- Lead-based Neutrino Detectors
- HALO at SNOLAB
- HALO-1kT at LNGS (LoI state)
- Risk Mitigation Strategies
- HALO-1kT Status

Supernova Neutrinos

- our only window into core-collapse supernovae (CCSNe) dynamics
- also a CCSN is the only place where:
  - matter is opaque to neutrinos and they thermalize yielding information about the proto-neutron star environment
  - neutrino density is so large that they interact through collective phenomena resulting in spectral splits and flavour swapping
  - the low temperature, high density part of the QCD phase diagram can be explored where there are predictions of nuclear matter → quark matter phase transitions

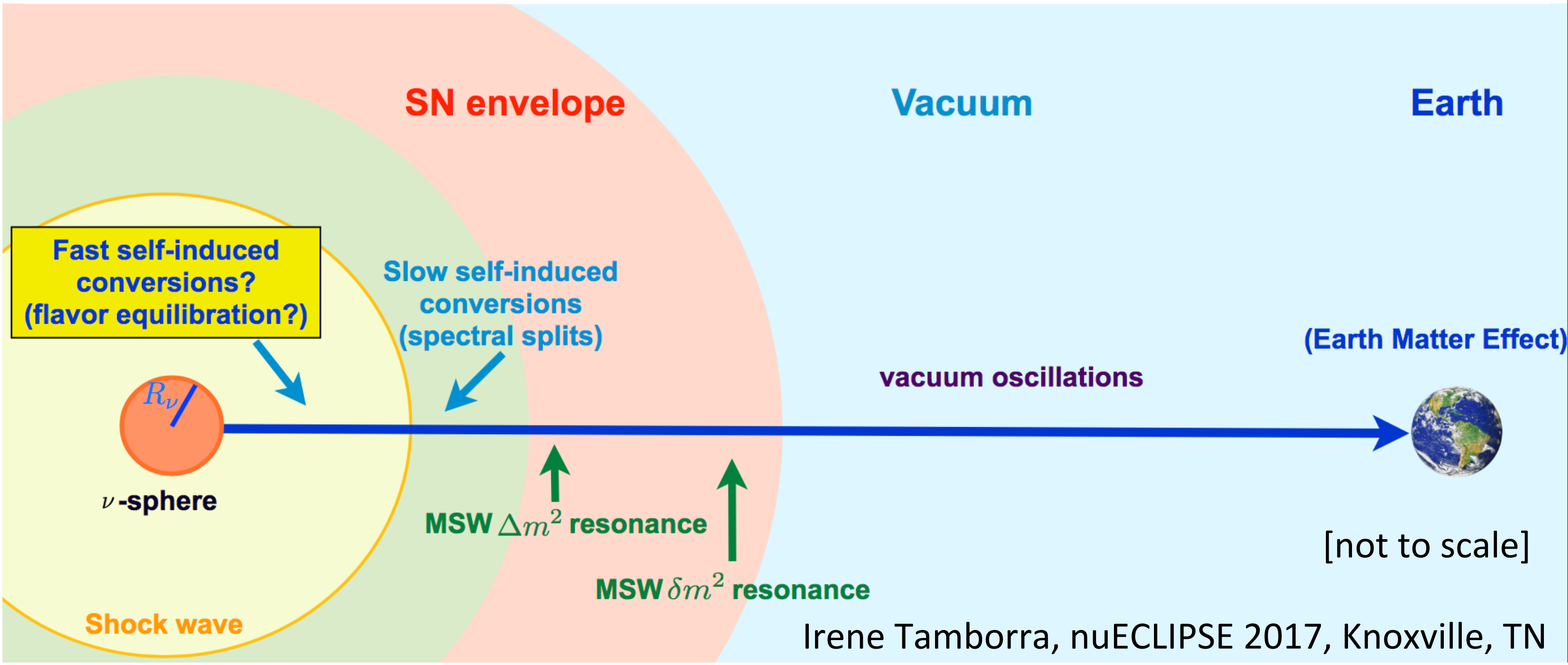




- we start with Fermi-Dirac distributions at the neutrino-spheres with:

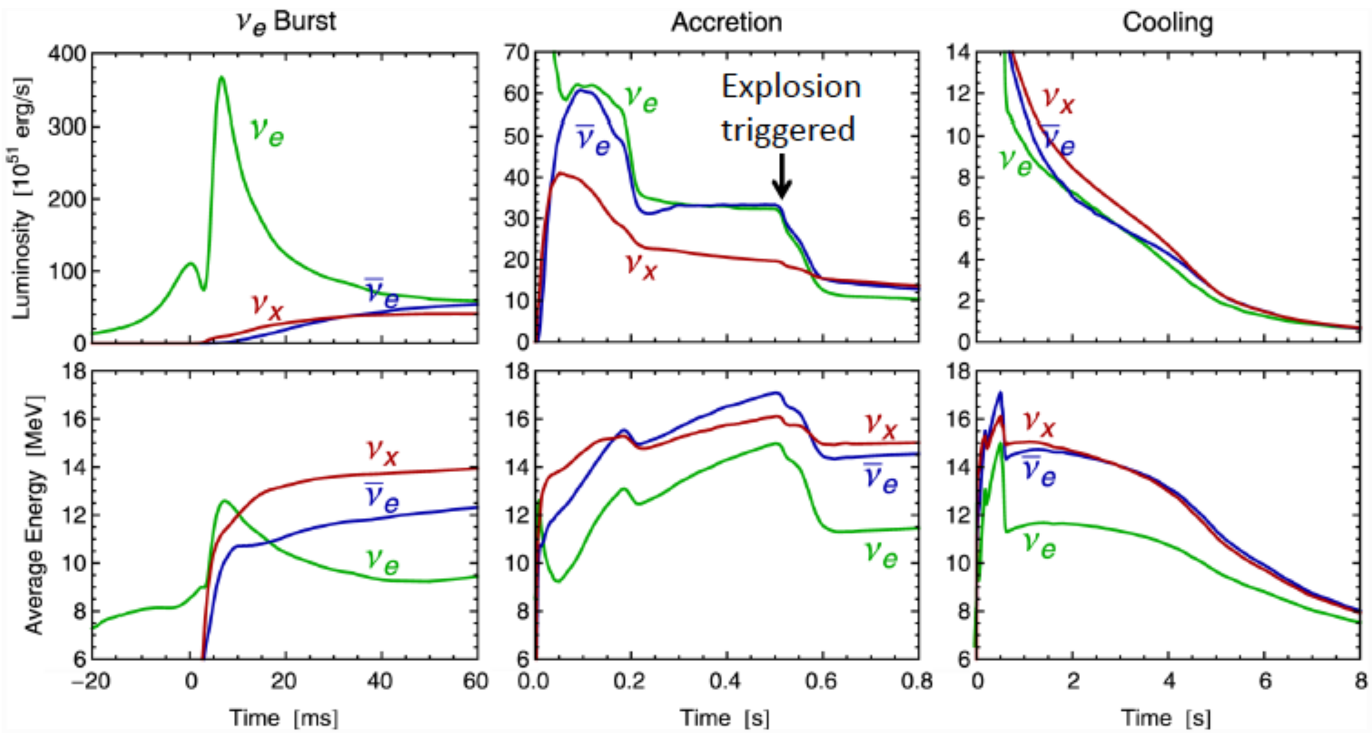
  $T(\nu_e) < T(\overline{\nu}_e) < T(\nu_x)$
- this signal is imprinted with:
  - collective effects
  - MSW effects
  - shockwave effects
  - large scale density oscillations
  - vacuum oscillations

Simplified Picture of Flavour Conversions



- neutrino emission source at ν-sphere evolves with time
- large-scale hydrodynamic effects (instabilities, ringing, dipole oscillations) affect neutrino signal
- then any given detector terrestrial detector imperfectly records part of the signal
- what can any one detector do when the signal is spread across ν_e, $\overline{\nu}_e$, ν_x and the time evolution of their flux and energy spectra with marginal statistics?!

Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Georg Raffelt, MPI Physics, Munich NOW 2014, 7–14 Sept 2014, Otranto, Italy

The Trouble with Supernovae

Oct. 13, 2016

Hubble Reveals Observable Universe Contains 10 Times More Galaxies Than Previously Thought

- SNe are very frequent in our universe (1→10? per second)
- Current and next generation terrestrial supernova neutrino detectors only see supernovae within our galaxy (tiny part of the universe)
- So.... The galactic core-collapse supernova rate is estimated, Adams et al., ApJ, **778**, 2, 164, (2013), at

$$3.2^{+7.6}_{-2.6} \text{ per century}$$

so… observing the neutrino signal requires some patience

Lead-based Supernova Detector

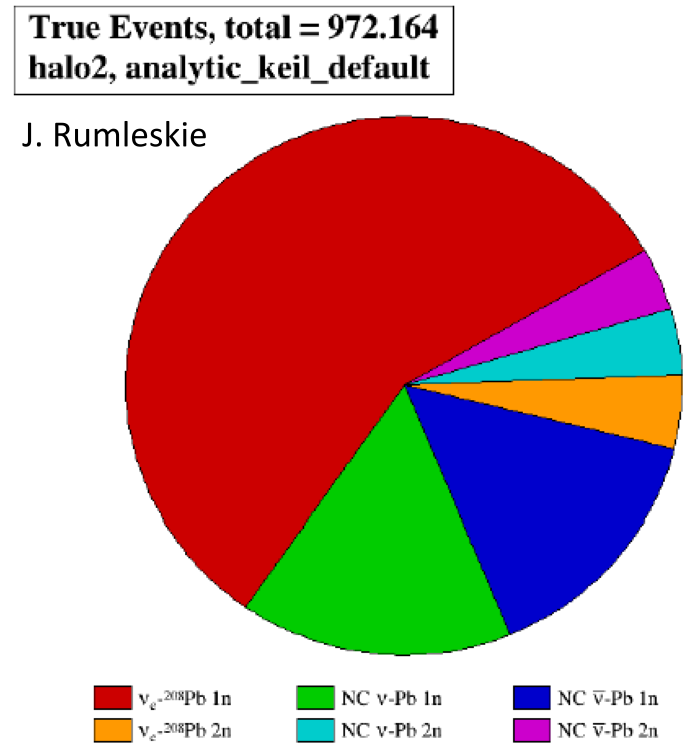
- set of detectors currently participating in SNEWS – Super-Kamiokande, LVD, Borexino, IceCube, KamLAND, Daya Bay, HALO
- with exception of HALO all are Liquid Scintillator (LS) or Water Cherenkov (WC) and are dominantly sensitive to the $\overline{\nu}_e$ flux through IBD
- lead-based SN detectors are $\overline{\nu}_e$ - blind, i.e. complementary
- reactions

$$\begin{aligned}
\mathrm{CC:}\quad & \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV} \\
& \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV} \\
\mathrm{NC:}\quad & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV} \\
& \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}
\end{aligned}$$

- electrons carry energy information and can 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 thermalisation
  - no energy measurement, though some sensitivity through 1n / 2n ratio
  - no direction measurement
  - only counting as a function of time

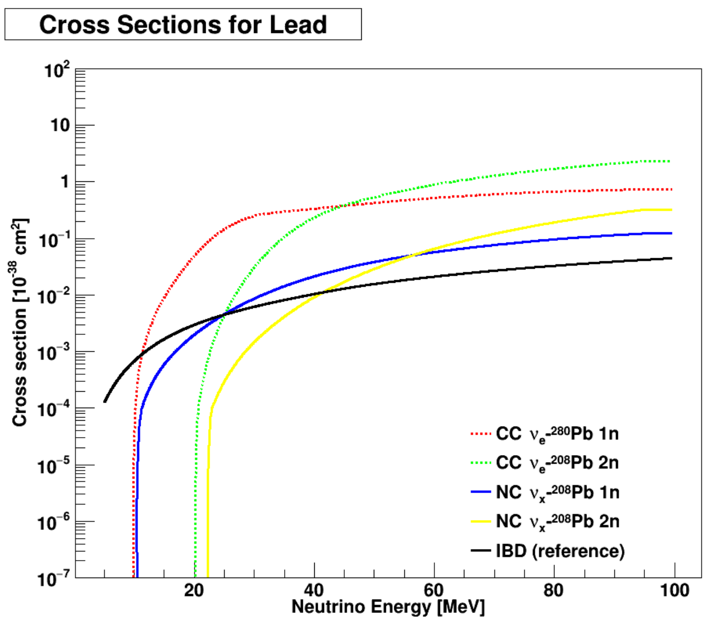
HALO / HALO-1kT Flavour Sensitivity

- the scientific merit of a lead-based supernova detector rests on its complementary flavour sensitivity wrt LS and WC detectors and the power that it brings to joint analyses
- the neutron excess in Pb Pauli blocks $\bar{\nu}_e$ CC reactions
- the high Z further Coulomb suppresses $\bar{\nu}_e$ 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 LS and WC



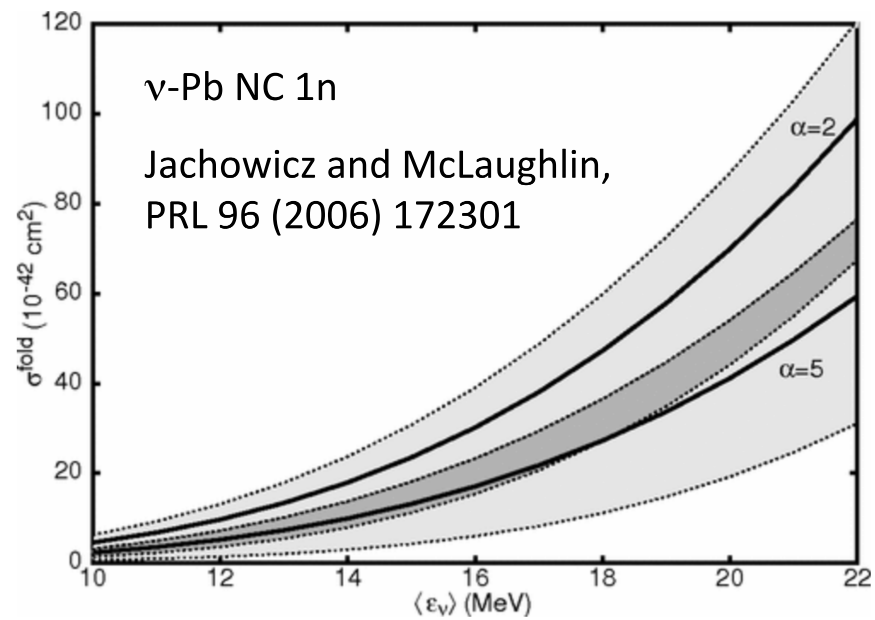
for 10 kpc, 100% efficiency, and power law spectra with α = 3 where
$\langle E\nu_e \rangle$ = 12 MeV or $T\nu_e$ = 3.8 MeV
$\langle E\bar{\nu}_e \rangle$ = 15 MeV or $T\bar{\nu}_e$ = 4.8 MeV
$\langle E\nu_x \rangle$ = 18 MeV or $T\nu_x$ = 5.7 MeV

ν-Pb Cross Sections and Uncertainties



SNOwGLoBES -
ν-Pb cross sections from Engel, McLaughlin, Volpe, PRD 67 (2003) 013005

- unmeasured, calculated only
- thresholds known
- less theoretical uncertainty near threshold
- more uncertainty away from threshold



Flux-averaged ("folded") cross sections as a function of $<E_\nu>$ for power law spectra and different α showing the theoretical uncertainty in response
Risk#1 – uncertainty in observed statistics for a given SN distance (mitigation later)

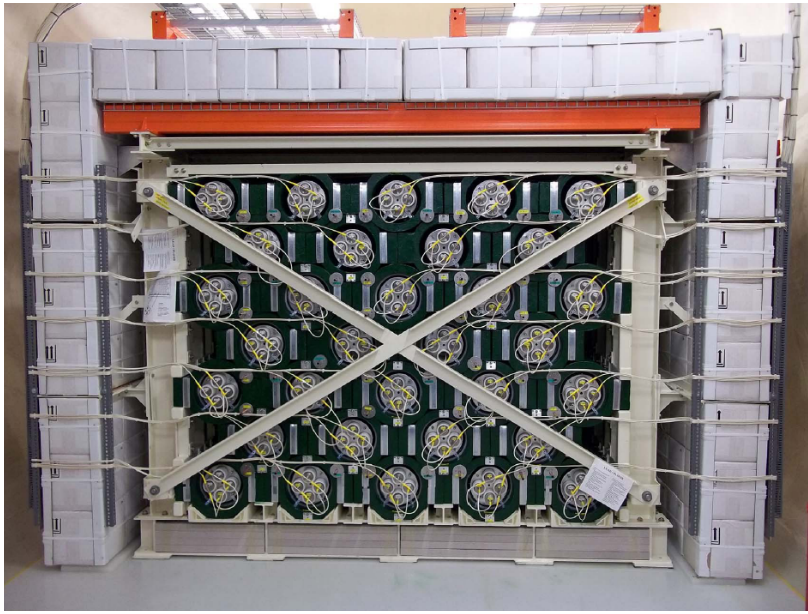
HALO - a Helium and Lead Observatory

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 ^3He neutron detectors from the final phase of SNO

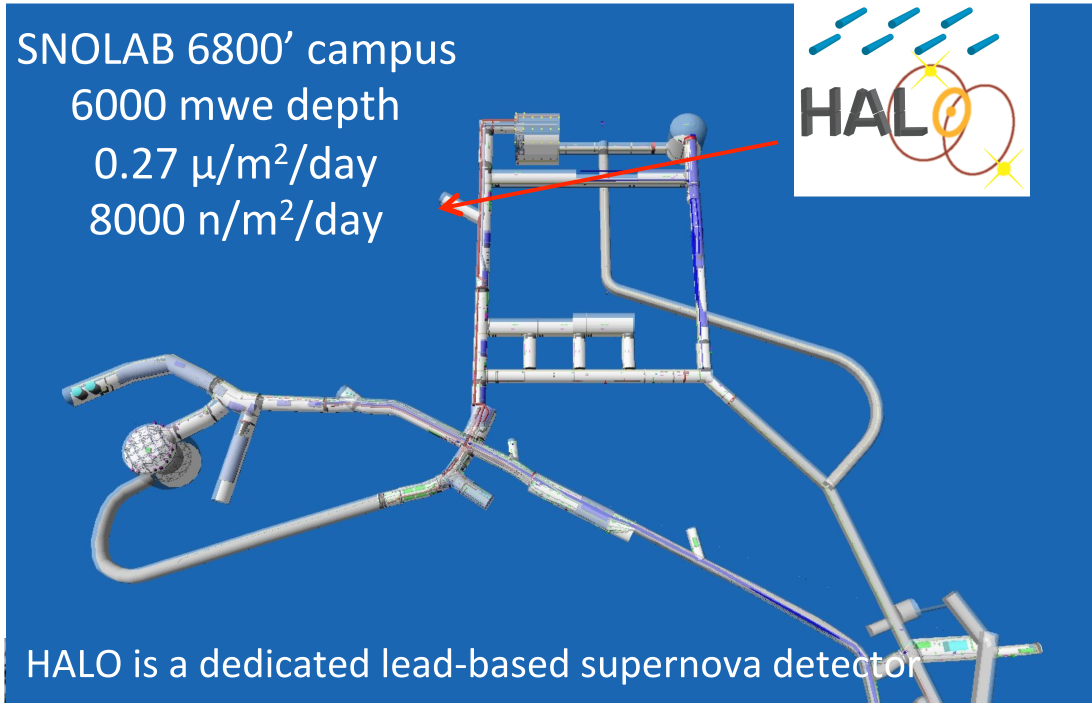
+

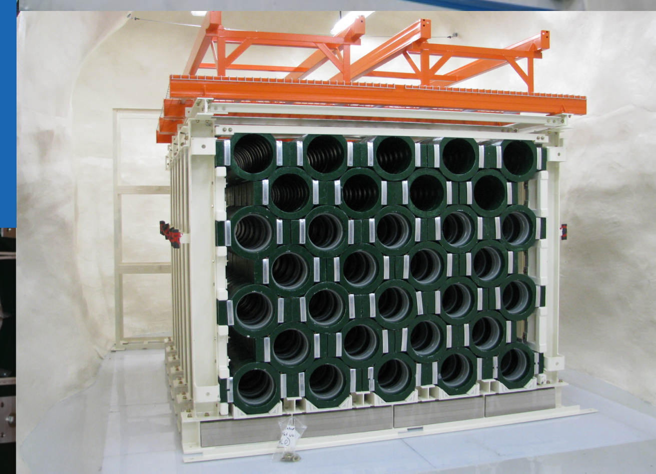
"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



HALO recycled lead blocks from a decommissioned cosmic ray monitoring station

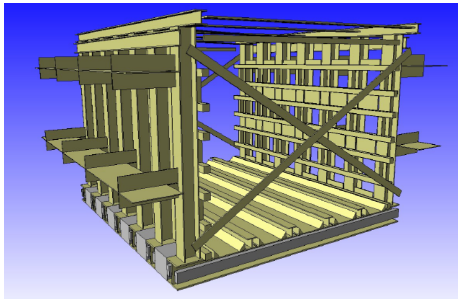
HALO at SNOLAB

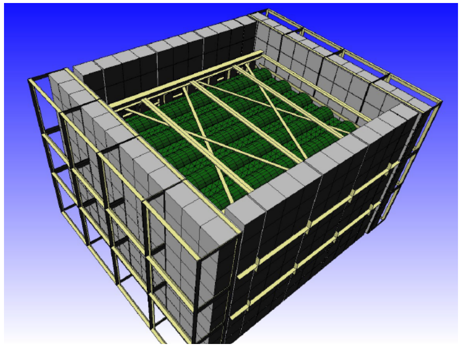


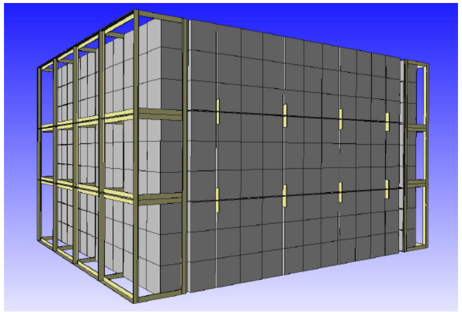


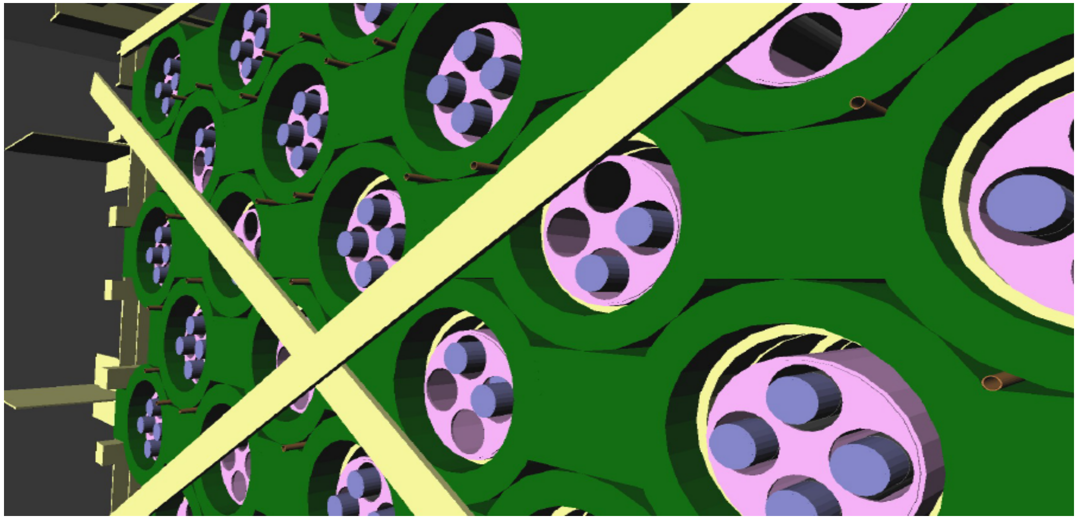
HALO at SNOLAB as a Prototype

- 79 tonnes of Pb
  - non-optimum lead geometry
  - instrumented with excellent low background neutron detectors (370 m containing ~1465 litre.atmospheres ^{3}He)
- operating since May 2012
- participating in SNEWS since October 2015
- simulated / calibrated / understood
- many redundant systems for reliability



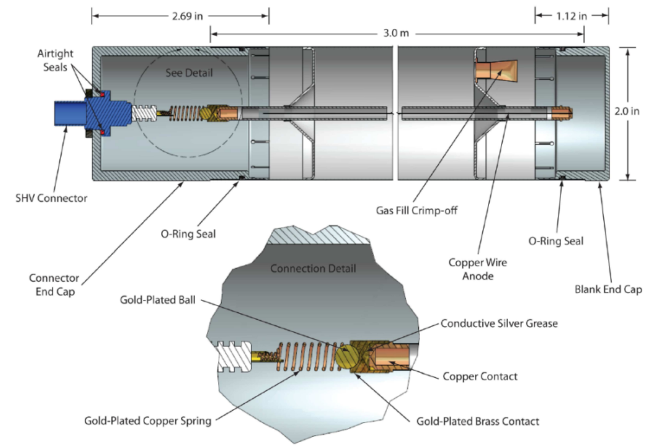


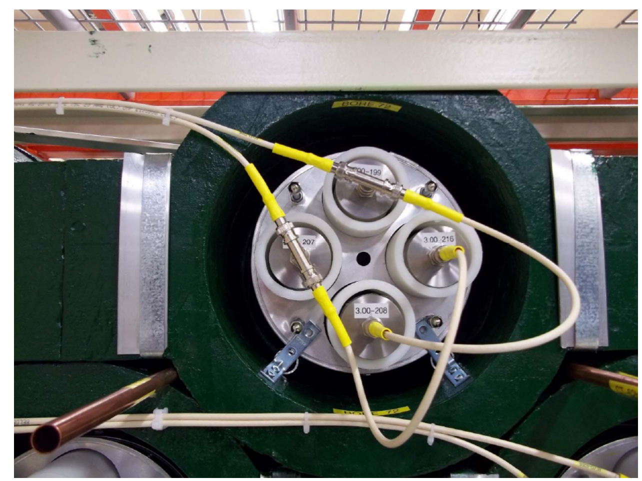




Neutron Detection in HALO

- 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



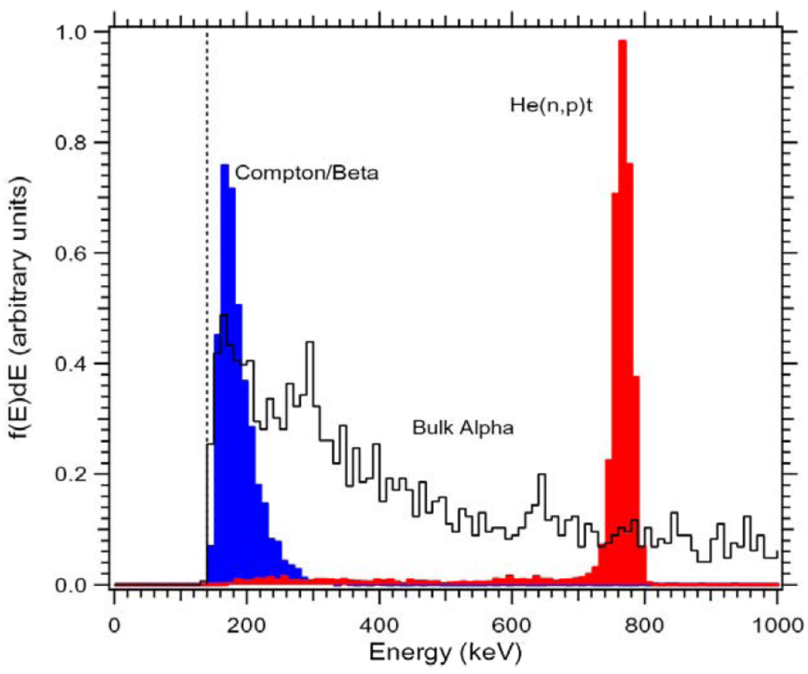


Neutron Detection in HALO

- Neutron detection via

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

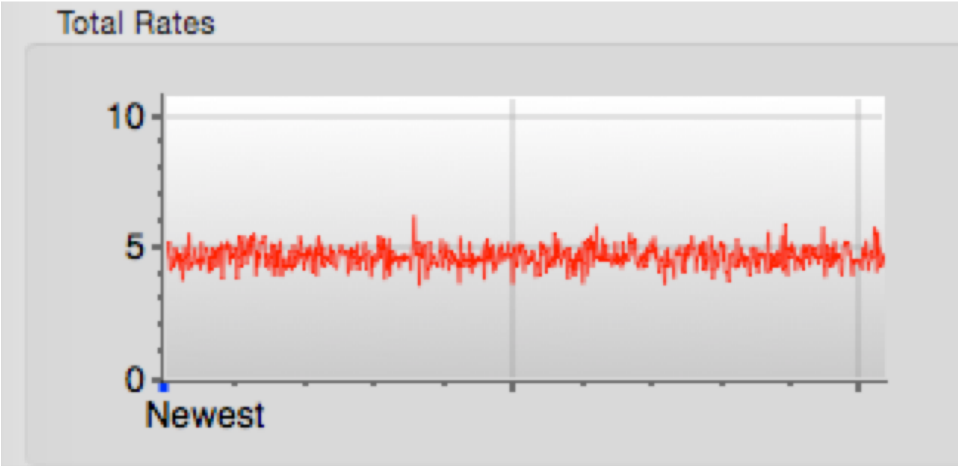
- 764 keV FE peak plus LE tail due to wall effects
- Compton and beta events at low energies
- Background n's in SNOLAB at level of 4000 fast plus 4000 thermal per m^2 per day.
- Cosmic muons < 2 per day
- Intrinsic tritium rate (18.6 keV endpoint) above 12 keV threshold ~10 Hz / detector but running at threshold of ~50 keV



Background Breakdown

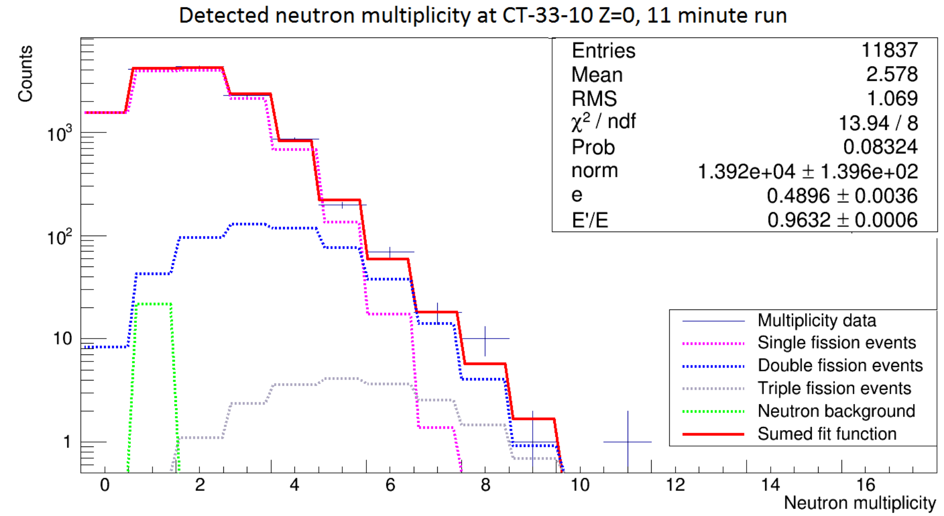
- Current "neutron" rate in HALO is 0.015 Hz (1294 ± 8 / day), or ~1 neutron per channel per hour, of which:
  - 23 ± 5 from ^{238}U spontaneous fission
  - 80 ± 43 from nearby stored ^{252}Cf calibration source
  - ~20 from internal α-emitting radio-contaminants
  - rest from leakage of environmental neutrons through shielding

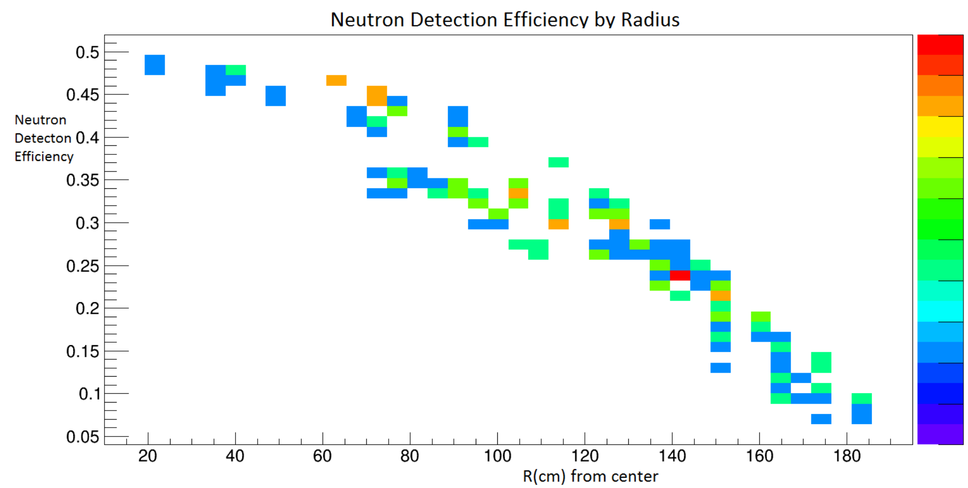
channel thresholds adjusted for even rates across channels and total rate of 5 Hz



HALO Calibration with ^{252}Cf Source

- 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





Redundancy

- the basics
  - power
    - UPS with ~3 hours runtime; automated shutdown and restart around extended power failures
    - in < 2 years SNOLAB will have 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 (time)
    - two units – surface and underground
    - ovenized oscillator in underground one in case fiber to surface lost
    - synchronization with HALO via ntp
    - good to better than 100 μs, cf 200 μs neutron capture lifetime

Redundancy

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

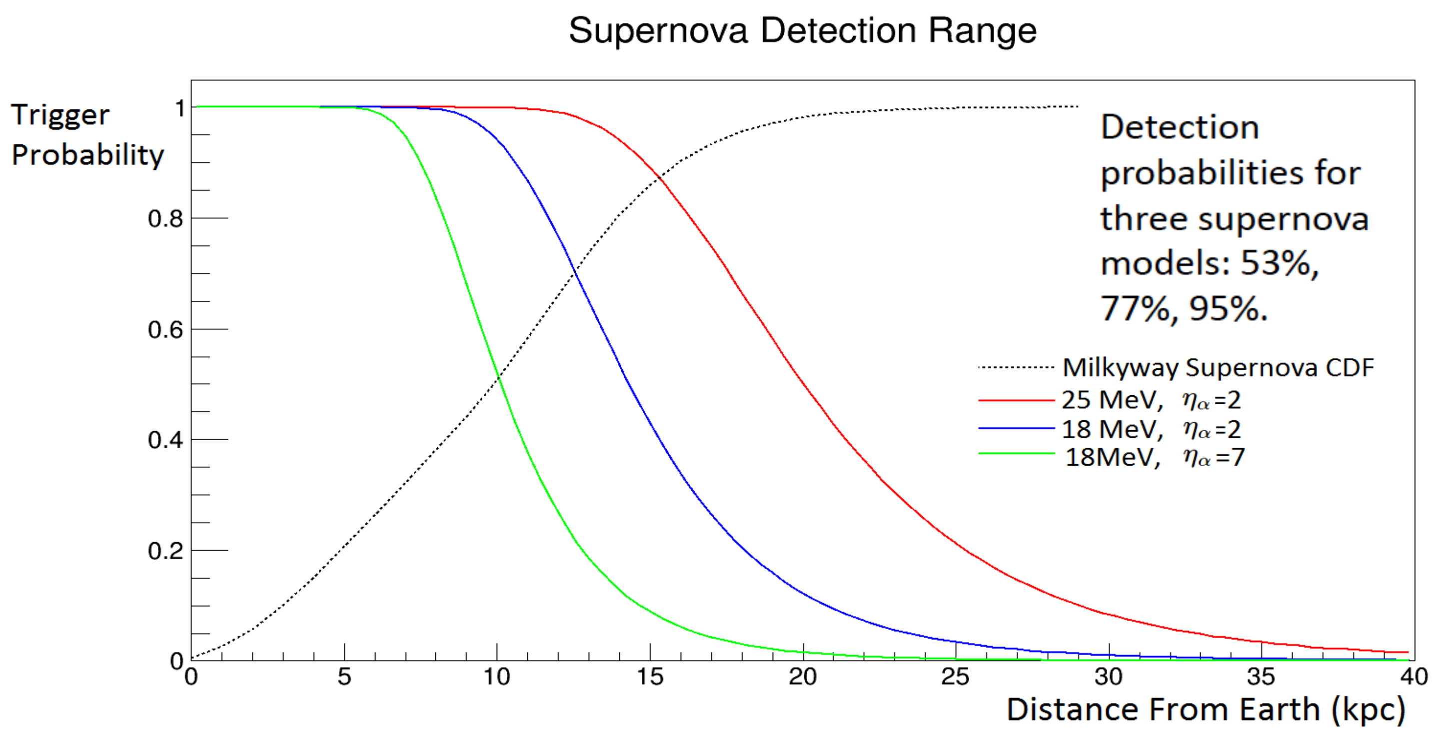
Required (one of):
- LV preamp power supply
- HV supply
- ADCs
- DAQ computer

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

SNEWS

- HALO's SNEWS Trigger is running stably, bursts classified and sent out via email to HALO list, data archived in "burst" files
- integrated with SNEWS alerts since October 2015



What is to be Learnt?

- 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.

Accessible Measurements

It is our premise that $\overline{\nu}_e$ sensitivity alone can not address all topics of interest and that data from HALO / HALO-1kT, with its complementary sensitivity, could be key. From our Letter of Intent such topics include:

- Observation of the ν_e burst from the initial 20 ms long neutronization phase would be a signal of an inverted neutrino mass hierarchy due to the non-zero ν_e MSW survival probability of $\sin^2 \theta_{12} \sim 0.3$. Non-observation of the ν_e burst implies a normal mass hierarchy, as the ν_e survival probability is zero in this case. Wallace, J., Burrows, A. and Dolence, J.C., Astrophys. J. **817** (2016) no.2, 182.
- Observation of an anomalously hot ν_e spectrum compared to $\nu_{\mu\tau}$ would be an indication of flavour-swapping and collective ν-ν effects at small radii in the supernova core. Duan, H, et al. , Ann. Rev. Nucl. Part. Sci. 2010.60:569, Fogli, G. et al., J. Cosmology & Astroparticle Physics **12** (2007) 010

Accessible Measurements - 2

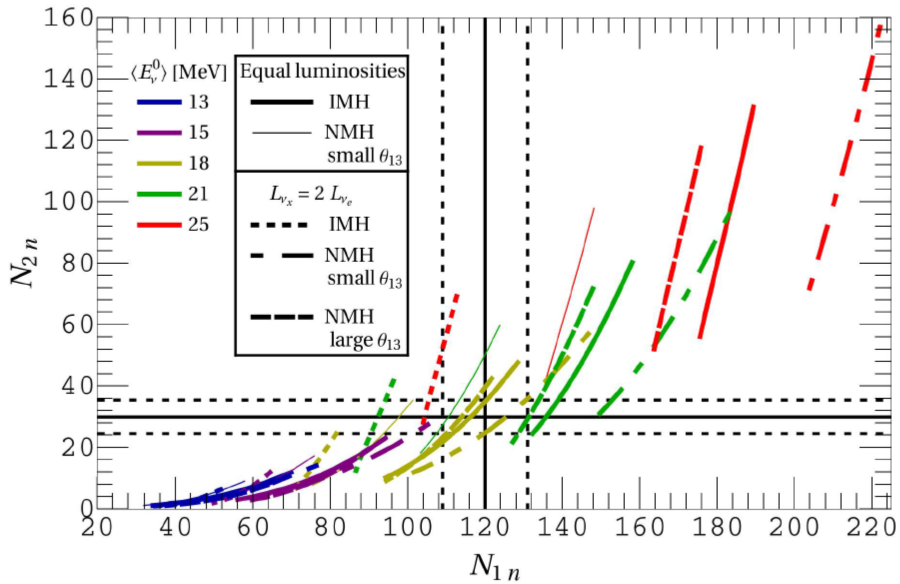
- Observation of a non-thermal neutrino spectrum or an anomalously large number of high-energy neutrinos would be an indication of the failure to trap and thermalize neutrinos in the supernova core (anomalously weak ν-nucleus interactions). Raffelt, G., Nucl. Phys. B (Proc. Suppl.) **221** (2011) 218
- Observation of the ratio of ν_e / anti-ν_e fluxes sets a constraint on the neutron flux available for r-process nucleosynthesis in supernovae since the ratio determines the relative charged-current conversion rate of neutrons to protons and protons to neutrons. Fischer, T., et al., Journal of Physics: Conference Series **665** (2016) 012069 .

Accessible Measurements - 3

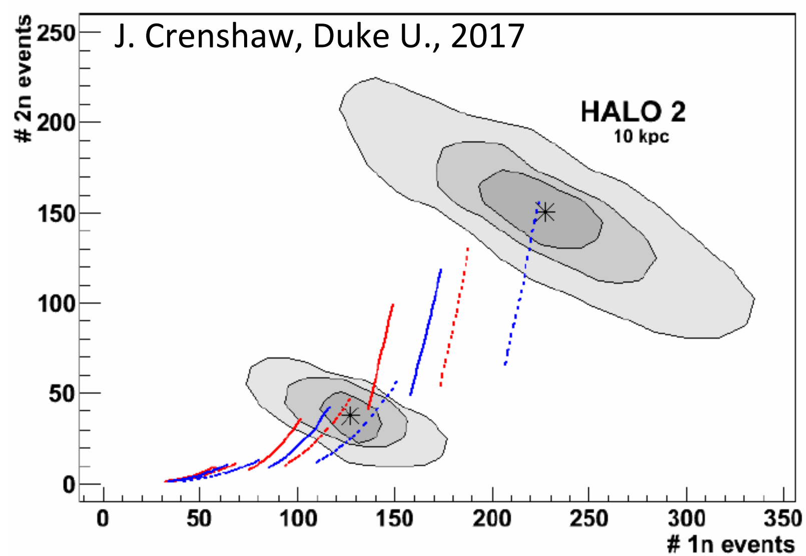
- Measurement of the shape (pinching) parameter of the neutrino energy spectrum gives an indication of how much the ν-nucleus interaction strength varies with changing ν energy. This provides possible sensitivity to nuclear pasta phases, where the neutrino opacity of the nuclear matter would increase as the de Broglie wavelength of the neutrinos becomes similar to the dimensions of the nucleon chains and sheets that compose the pasta C.J. Horowitz et al, PRL **114**, 031102 (2015). Observing the ratio of 1-neutron to 2-neutron emission events in HALO constrains the parameter space of $\langle E_\nu \rangle$ versus shape parameter Vaananen, D., and Volpe, C., JCAP **1110** (2011) 019
- more in LoI

Ability to Determine <$E_{\nu x}$> and $\alpha_{\nu x}$

- Monte Carlo study for HALO-1kT at 10 kpc
- observed 1n and 2n events unfolded to get true event ratios
- contours are 90% confidence limits for neutron capture efficiencies of 40%, 60% and 80%
- large part of parameter space can be excluded at 10 kpc, with realistic efficiencies



Vaananen, D., and Volpe, C., JCAP 1110 (2011) 019

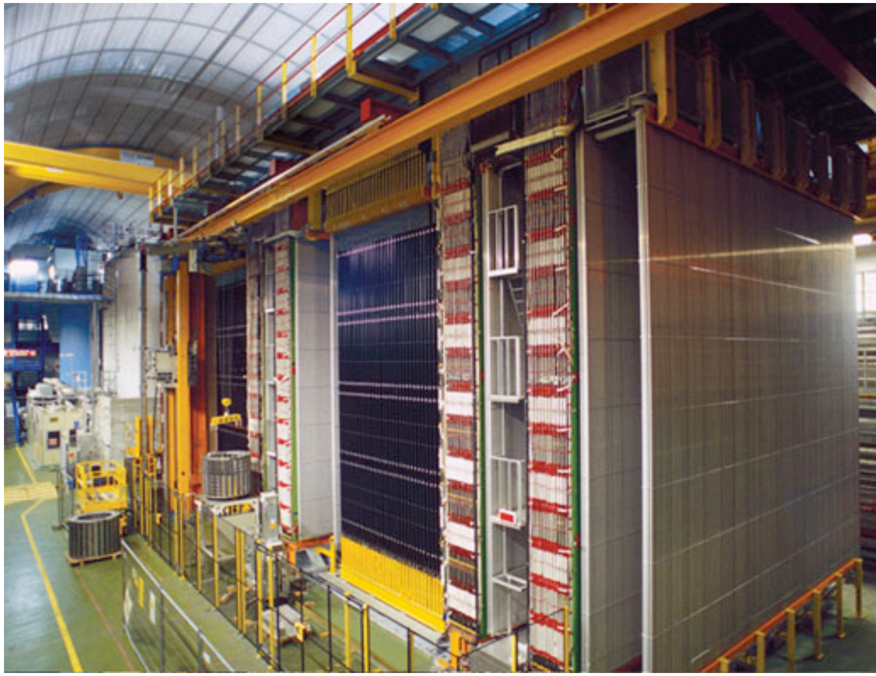


$\epsilon = 0.4, 0.6, 0.8$

HALO-1kT at LNGS

- scale up HALO keeping many design principles
- apply lessons learnt to make improvements
  - increase mass 79 → 1000 (factor of 12.7)
  - increase efficiency 28% to >50% (factor > 1.8)
- ~23 fold-increase in event statistics over HALO

Risk #2 - not achieving the high efficiency seen in simulations – mitigation later



The decommissioning of OPERA has made available 1300 tonnes of Pb

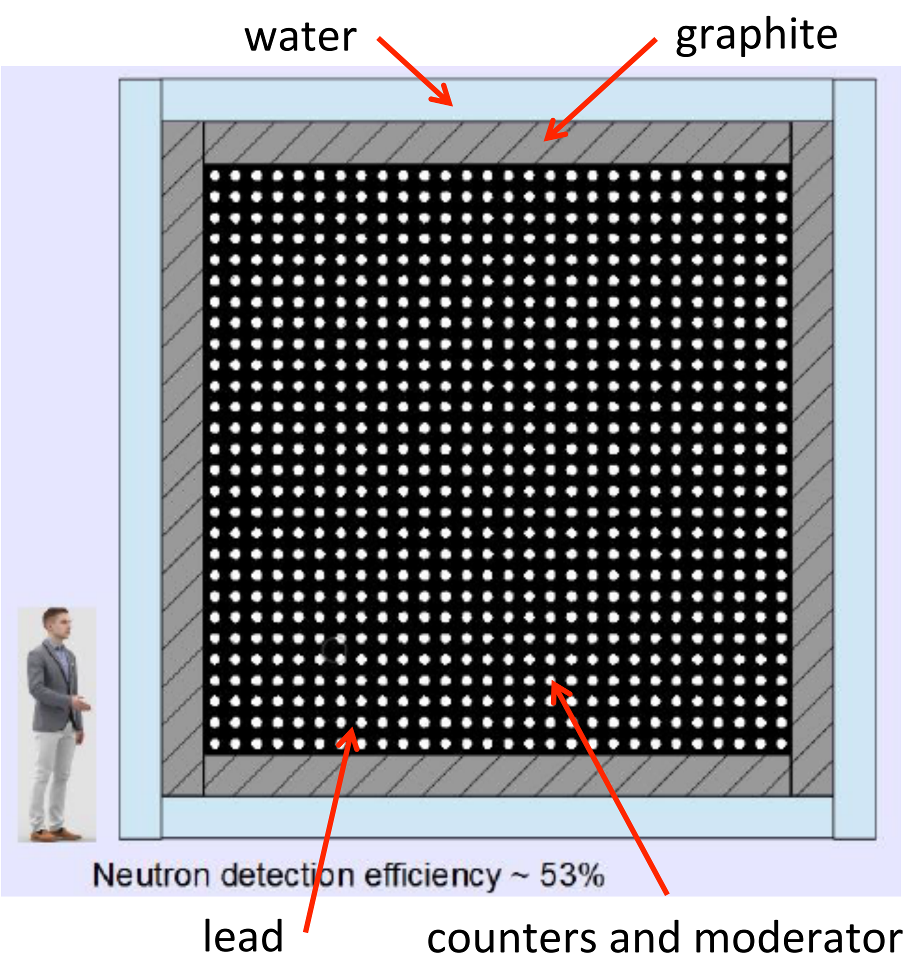
Simulation Studies

- constrain to 10,000 litre.atmospheres of ^{3}He; 1000 tonnes of lead; 5.5 m depth of lead volume / length of 3 standard ^{3}He counters
- 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 water shielding
  - more
- no consideration to backgrounds in these studies and the effect on neutron capture efficiency and participation in SNEWS

Risk#3 – various background sources (unsimulated) dictate a higher threshold for SNEWS and sensitivity not covering the whole galaxy – mitigation later

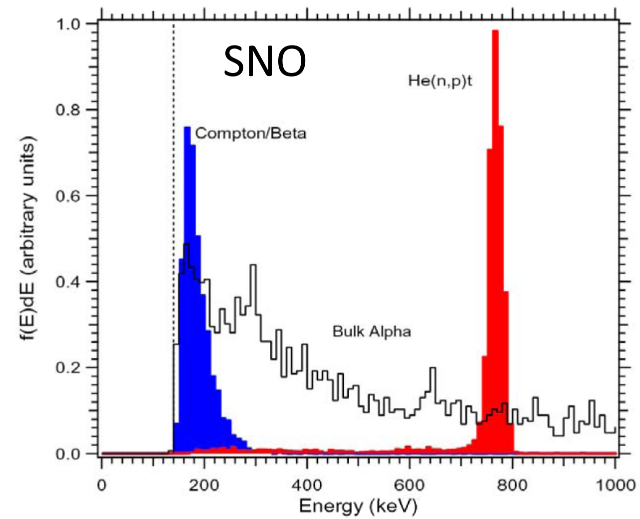
HALO-1kT Base Design

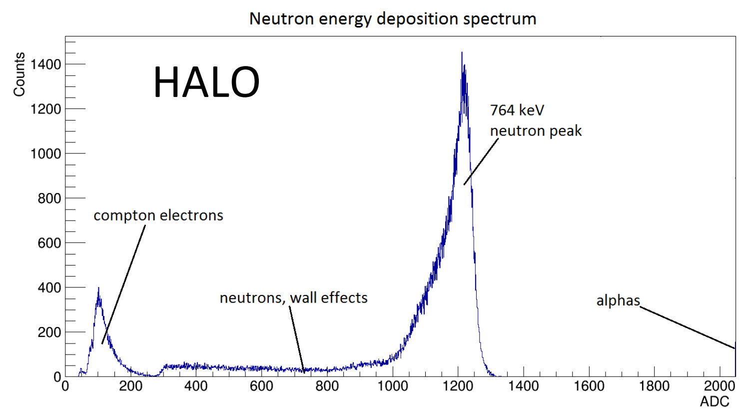
- lead core 4.33 x 4.33 x 5.5 m^3 with 28 x 28 x 5.5 m array of ^{3}He at 1.16 atm pressure
- 8 mm thick PS moderator
- no internal paint or coating / containment of lead blocks
- 30 cm graphite reflector
- 30 cm water shielding
- near final – two paths to finish exploring
  - changing total amount of ^{3}He – re-optimization required
  - proportional tube pressure (non-^{3}He component)
- reflector and shielding require further optimization once we have conceptual mechanical design for superstructure



Neutron Detector R&D

- HALO achieved good neutron – β / γ separation by shortening the ADC integration time
- in addition HALO-1kT has studied thinner, lower-Z tube walls, i.e. SS → Al
  - reduces β / γ above 50 keV
  - also reduces n-capture competition with ^3He
- and higher pressure fill gas
  - shortens p-t track lengths
  - moves neutron events from LE tail to FEP
  - ^4He looks interesting





Neutron / "Neutron" Backgrounds

- use SNEWS efficiency to far edge of galaxy to set background requirements for HALO-1kT
  - neutron / neutron-like events must be < 6.7 Hz in HALO-1kT for viable SNEWS trigger
  - employ a safety factor → go to 1 Hz max, extends trigger range by ~70%, or allows for the cross section to be a factor of 3 lower
  - any individual contributions < 10% of this, i.e. < 0.1 Hz

- cf HALO / NCDs (370 m array) Actuals
  - 1300 neutrons /day (0.015 Hz) of which
    - 23 ± 5 from ^{238}U spontaneous fission
    - 80 ± 43 from nearby stored ^{252}Cf calibration source
    - ~25 from neutron counter's internal α contamination
    - rest from leakage through shielding or (α,n) on internal materials
  - cosmic muons → spallation – few per month

Neutron / “Neutron” Backgrounds

- HALO-1kT (4312 m array) Budget
  - < 86400 neutrons/day (1Hz) of which
    - < 8640 /day from SF → sets a spec
    - < 8640 /day from internal α contamination
      - measurements on commercial test counters project to ~105,000 /day
      - need a factor of ~12 reduction → R&D next slide
    - < 8640 leakage through shielding → sets a spec
      - background in LNGS less
      - similar shielding, higher capture efficiency, but greater area, added reflector?
    - < 8640 neutrons from (α,n) on internal materials → sets several specs
    - < 8640 beta/Compton scatter events above 191 keV → R&D to minimize and sets several specs
  - QA program implied for material acceptance
  - cosmic muons
    - flux ~109 x greater than SNOLAB, detector larger mass → ~900/day resulting in ~100 spallation events/day but short capture time

Internal α's and P(^{3}He) Optimization

- α-counting on test counter from GE Reuter-Stokes so far suggests bulk U/Th contamination at the level of 100 ppb by mass for SS
- radiopurity.org suggests factor of 20-200 reduction possible with choice of SS stock
- this assumes that the tube walls are making the dominant contribution
- 6 counters of various wall materials and gas-fills on order for further tests

- increasing ^{3}He pressure in geometry optimized for 10,000 litre.atm shows only small improvement in efficiency
- need to repeat the optimization at a couple of other ^{3}He quantities to understand real slope of efficiency to ^{3}He, followed by a cost-benefit analysis to select amount of ^{3}He

Risk Mitigation Strategies

- Risk #1 – uncertainty in observed statistics for a given SN distance
  - Reduce uncertainty with a measurement of the ν-Pb cross sections at the ORNL SNS facility
- Risk #2 – not achieving neutron capture efficiency goals
  - use HALO as a component test bed for prototypes
  - continue MC development in parallel
  - make use of HALO experience
- Risk #3 – various background sources force a higher SNEWS trigger threshold
  - develop and set conservative specs on all contributing background sources
  - plan for a QA program for material selection

HALO-1kT Status

- have formed a new HALO-1kT Collaboration (growing – contact me!)
  - 10 existing HALO members (Cdn & US)
  - 8 new Italians
  - 6 new Canadians
  - 4 new Americans
- still in the "fun" conceptual stage – ~unconstrained but conscious that increasing costs diminish likelihood of realization
- goal is to achieve 50% neutron capture efficiency
- expressed an interest in the OPERA lead to the LNGS Scientific Committee in April 2015
- made a submission to the LNGS "10 year Plan for UG Resources" exercise in February 2016
- submitted an LOI to LNGS in March 2017; defended in Oct 2017
- producing Experimental Proposal on a 1 year timescale
- application for capital funding late 2018 or 2019
- in contact with US DOE Isotope Program re: ^{3}He

Fine / Grazie