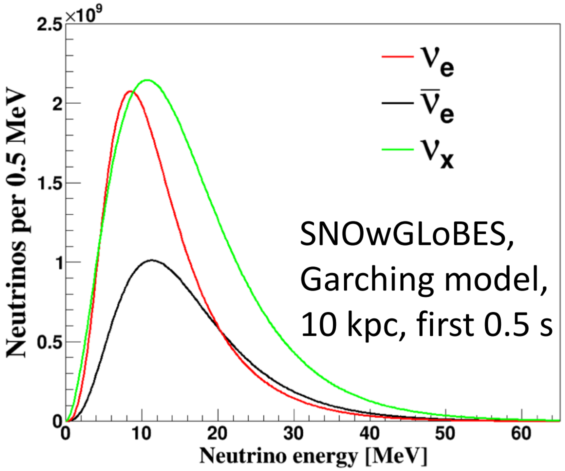
The HALO-1kT Supernova Neutrino Detector

C.J. Virtue for the Collaboration

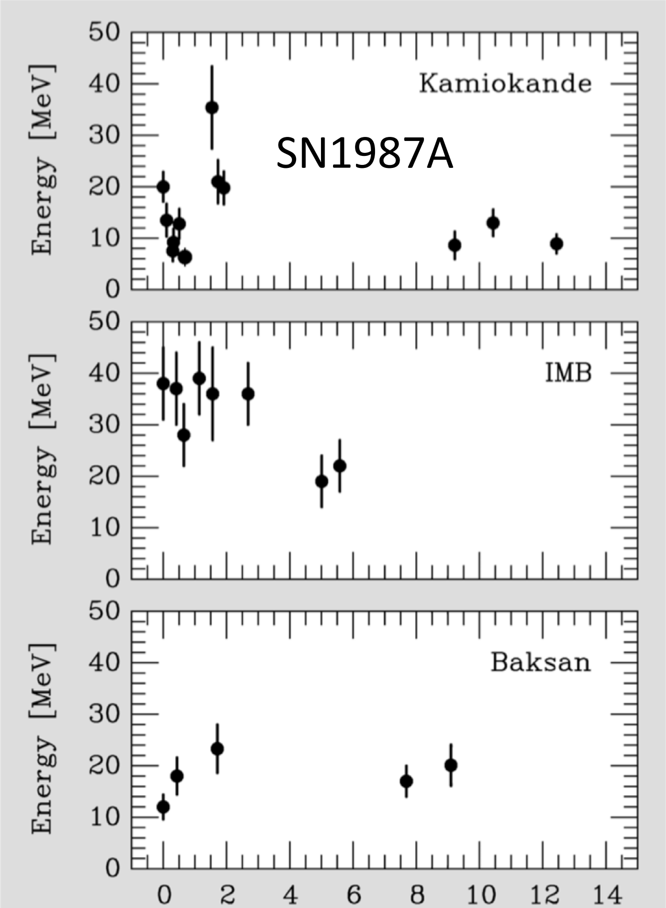
Supernova Neutrinos

- 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



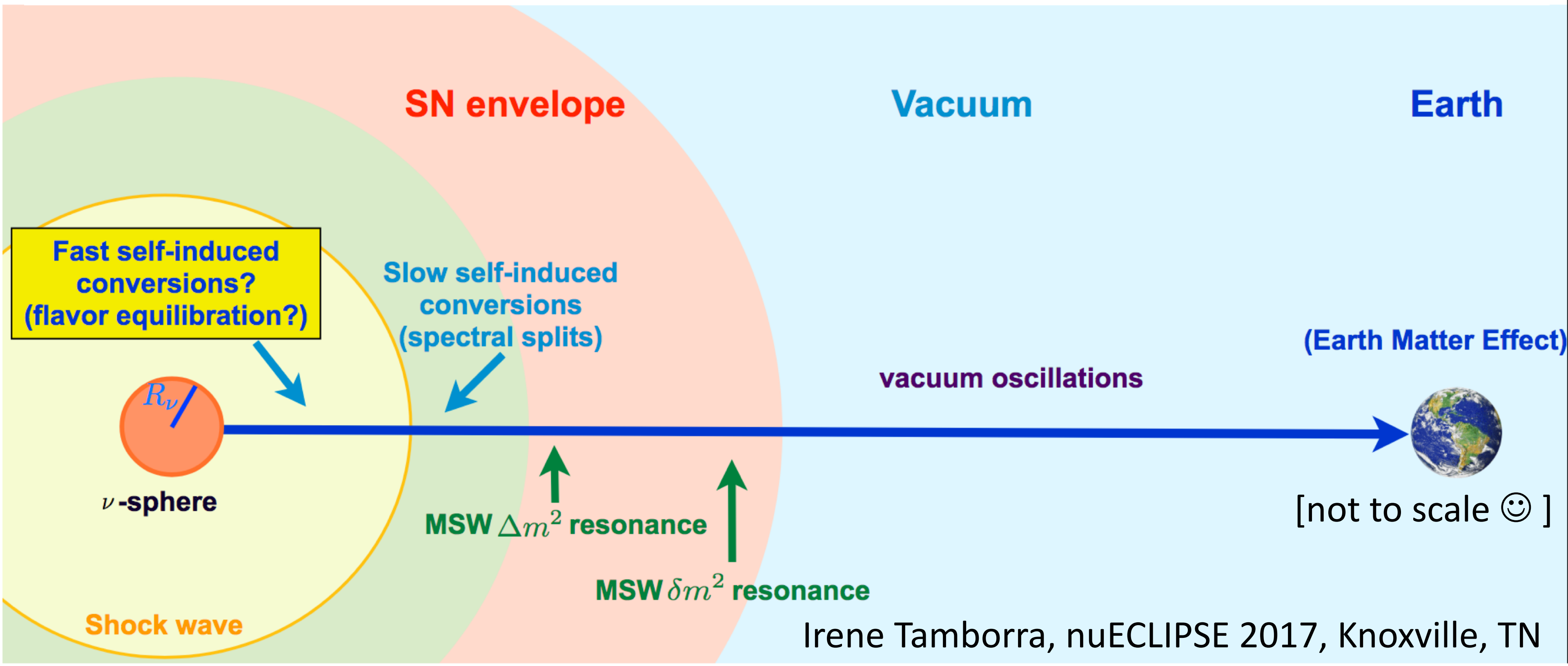
- we start with Fermi-Dirac distributions at the neutrino-spheres with:

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



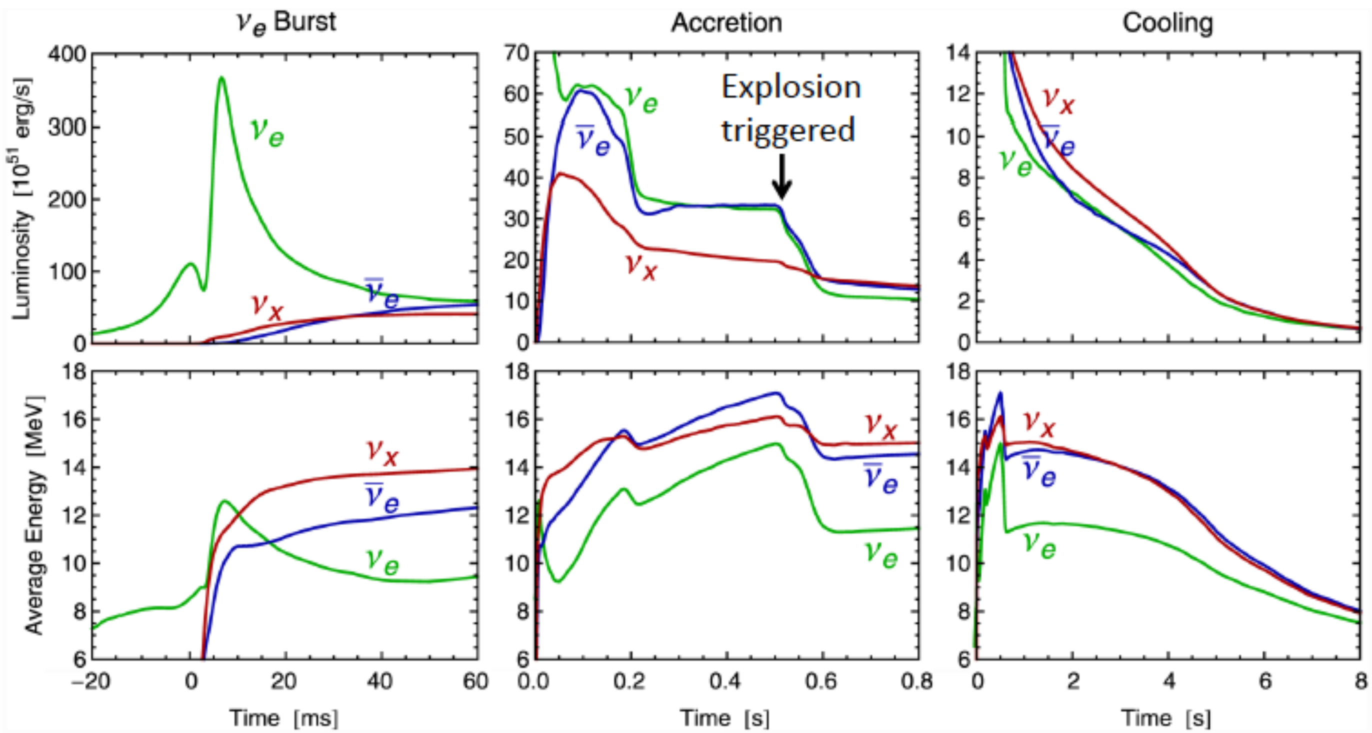
G. Raffelt

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

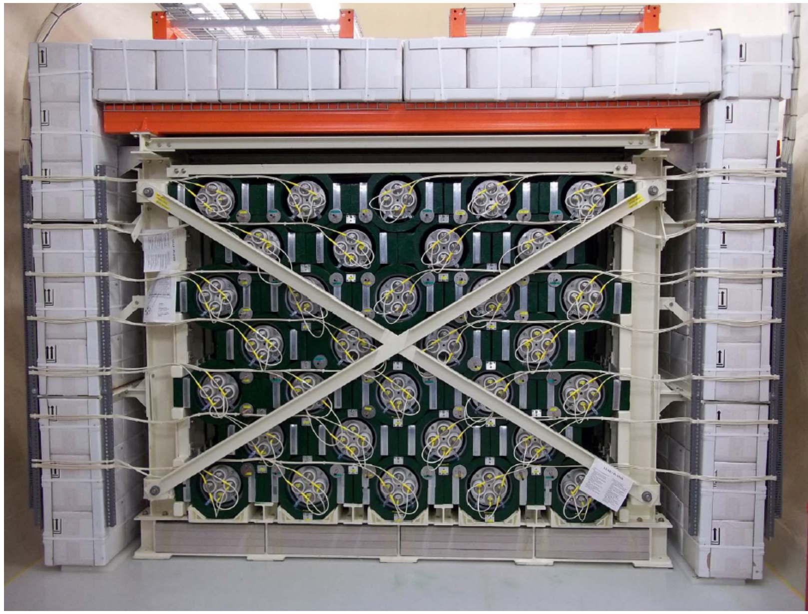
HALO - a Helium and Lead Observatory

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

+

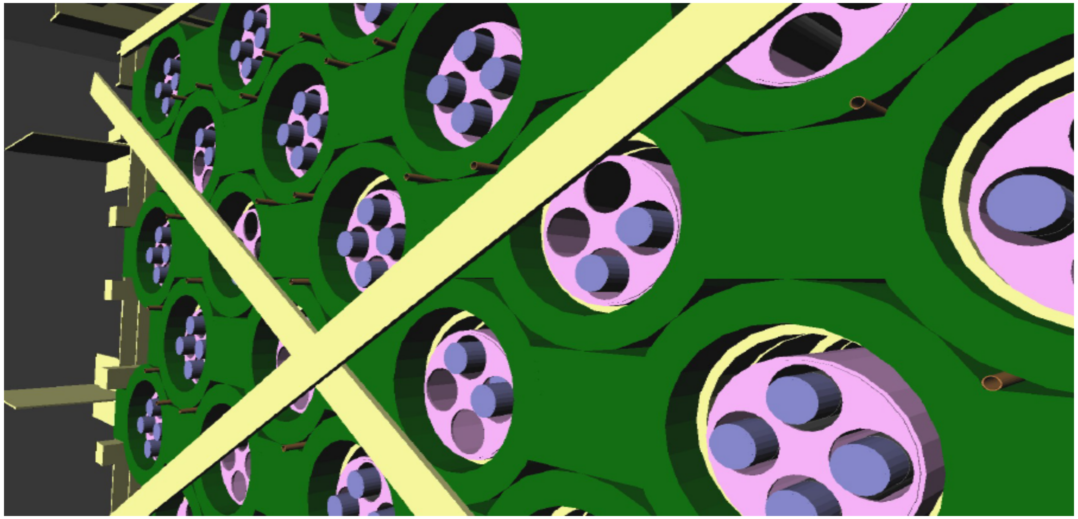
"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors

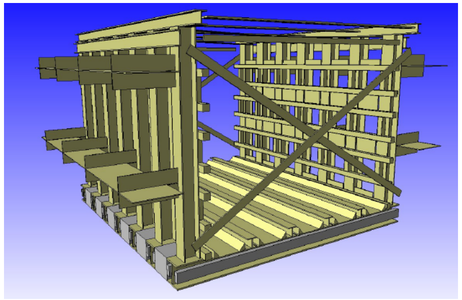


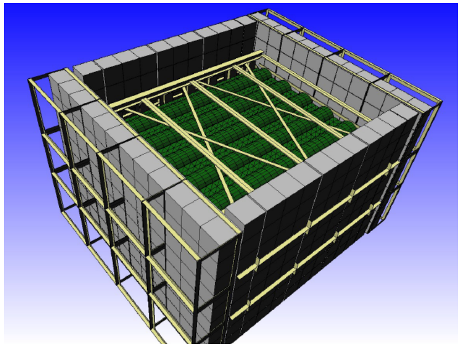
HALO recycled lead blocks from a decommissioned cosmic ray monitoring station

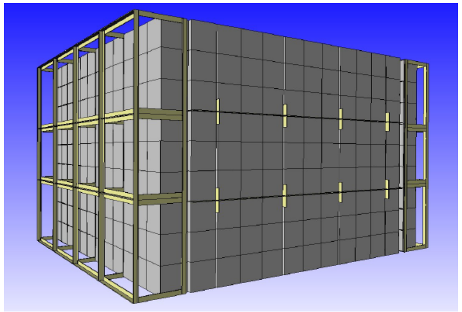
HALO at SNOLAB as a Prototype

- 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



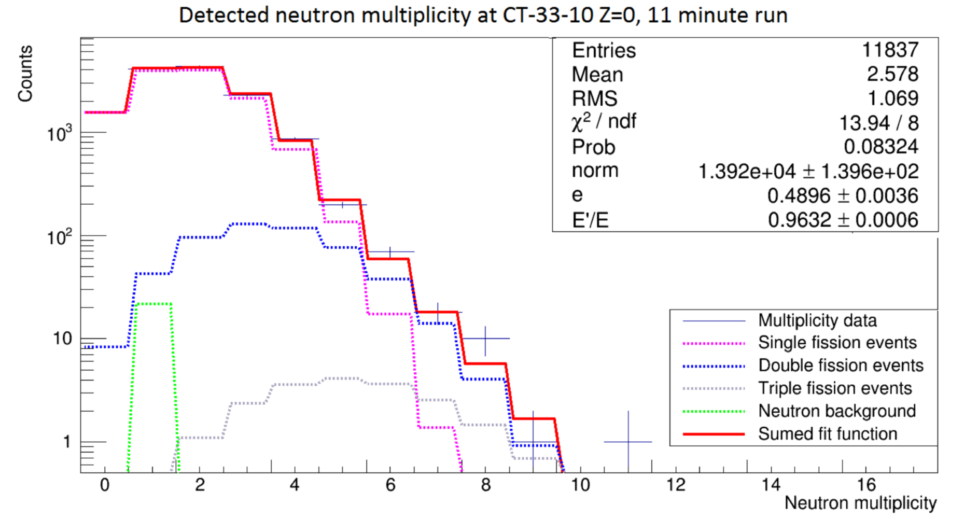


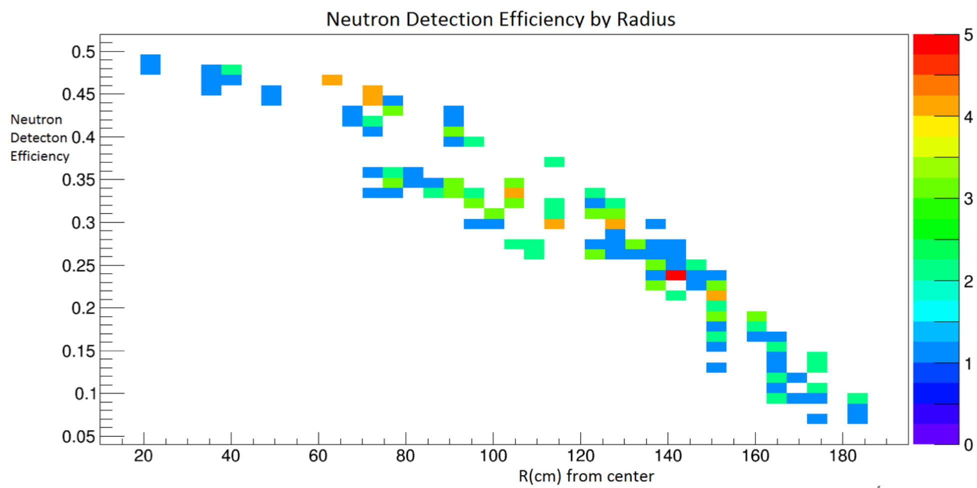




HALO Calibration with ^{252}Cf Source

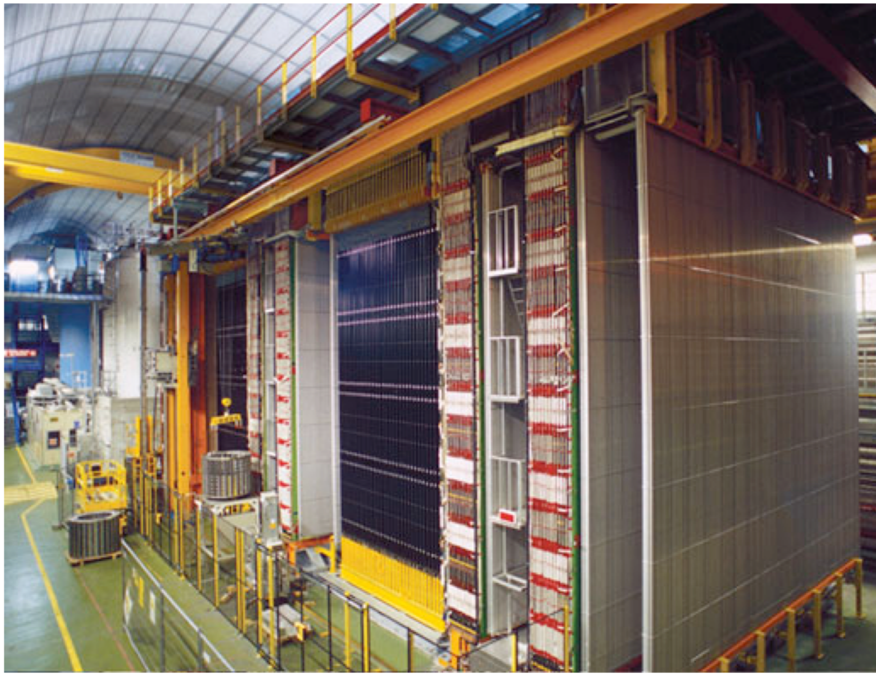
- used a low activity (~20 SF/s) ^{252}Cf source
- with very low backgrounds were able to measure the neutron multiplicity distribution which is a strong function of the neutron capture efficiency at 192 points
- extend time window to ensure that all neutrons from an integral number of fissions were 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





HALO-1kT at LNGS

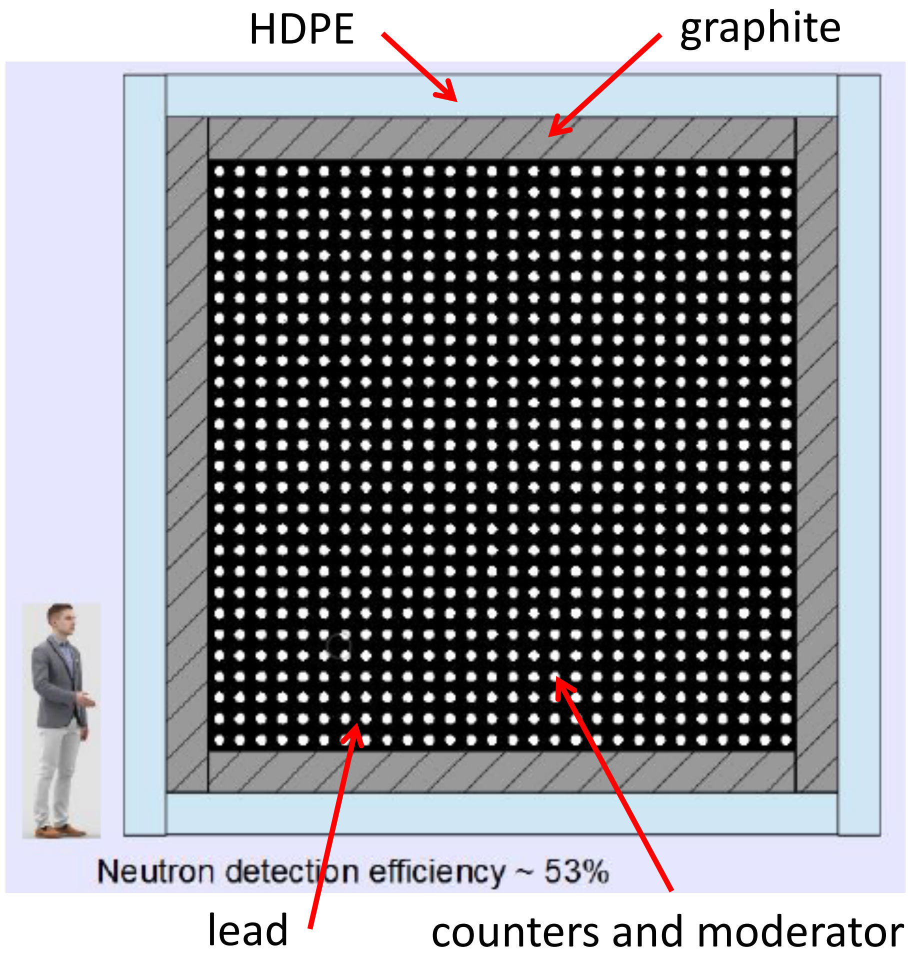
- scale up HALO keeping many design principles
- apply lessons learnt to make improvements
  - increase mass 79 → 1000 (factor of 12.7)
  - increase efficiency 28% to >50% (factor > 1.8)
- ~23 fold-increase in event statistics over HALO



The decommissioning of OPERA has made available 1300 tonnes of Pb

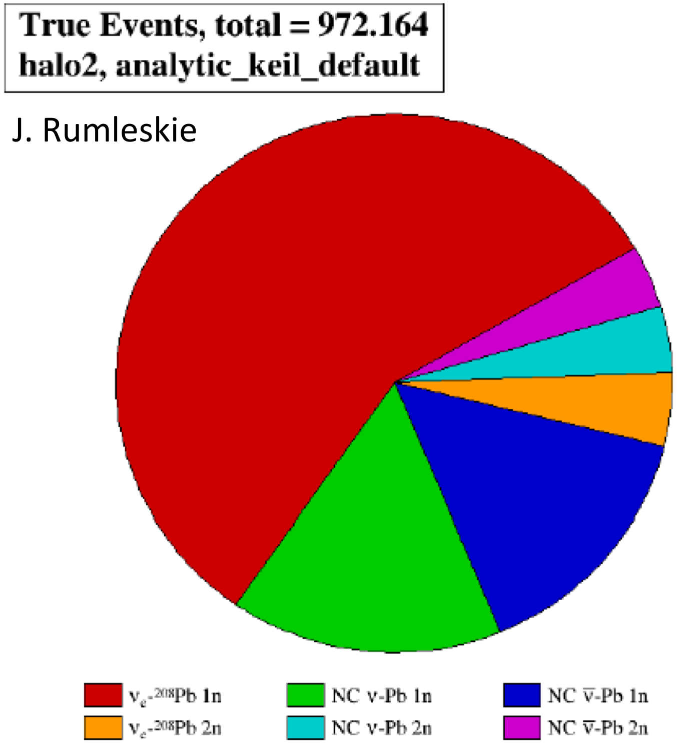
HALO-1kT Base Design

- 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 HDPE shielding
- reflector and shielding require further optimization once we have conceptual mechanical design for superstructure



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 $\overline{\nu}_e$ CC reactions
- the high Z further Coulomb suppresses $\overline{\nu}_e$ 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



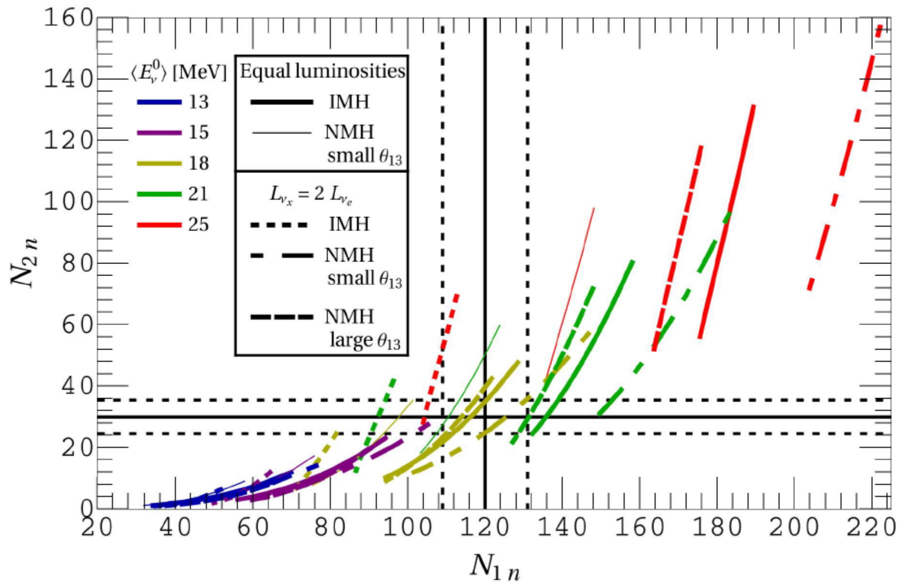
for 10 kpc, 100% efficiency, and power law spectra with α = 3 where
$\langle E\nu_e \rangle$ = 12 MeV or $T\nu_e$ = 3.8 MeV
$\langle E\nu_e \rangle$ = 15 MeV or $T\nu_e$ = 4.8 MeV
$\langle E\nu_x \rangle$ = 18 MeV or $T\nu_x$ = 5.7 MeV

What is to be Learnt?

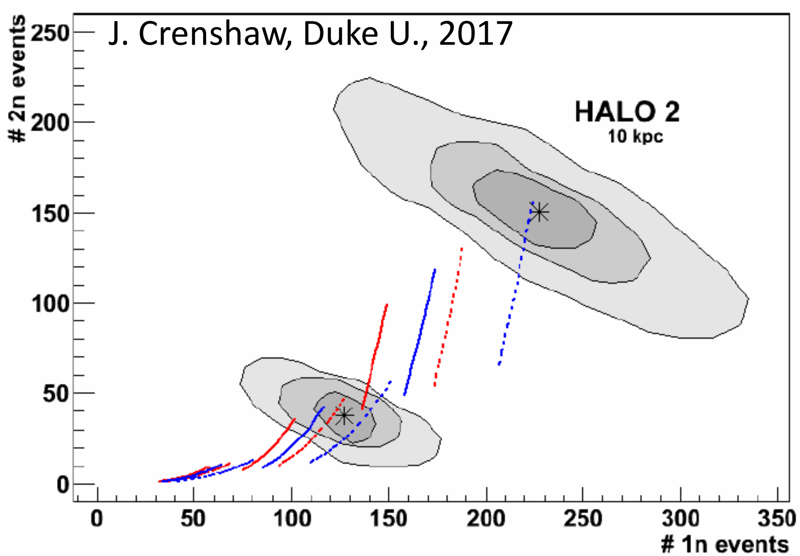
- Astrophysics
  - Explosion mechanism
  - Accretion process
  - Black hole formation (cutoff)
  - Presence of Spherical accretion shock instabilities (3D effect)
  - Proto-neutron star EOS
  - Microphysics and neutrino transport (neutrino temperatures and pinch parameters)
  - Nucleosynthesis of heavy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

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

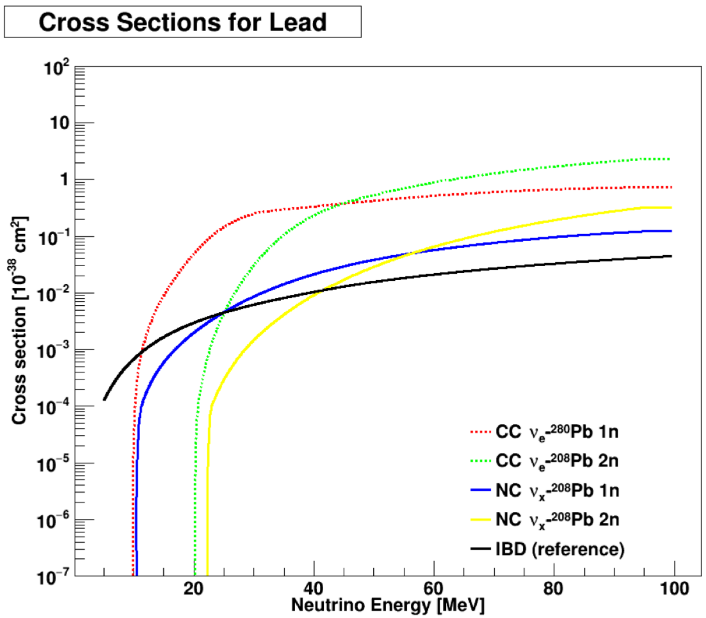


Vaananen, D., and Volpe, C., JCAP 1110 (2011) 019



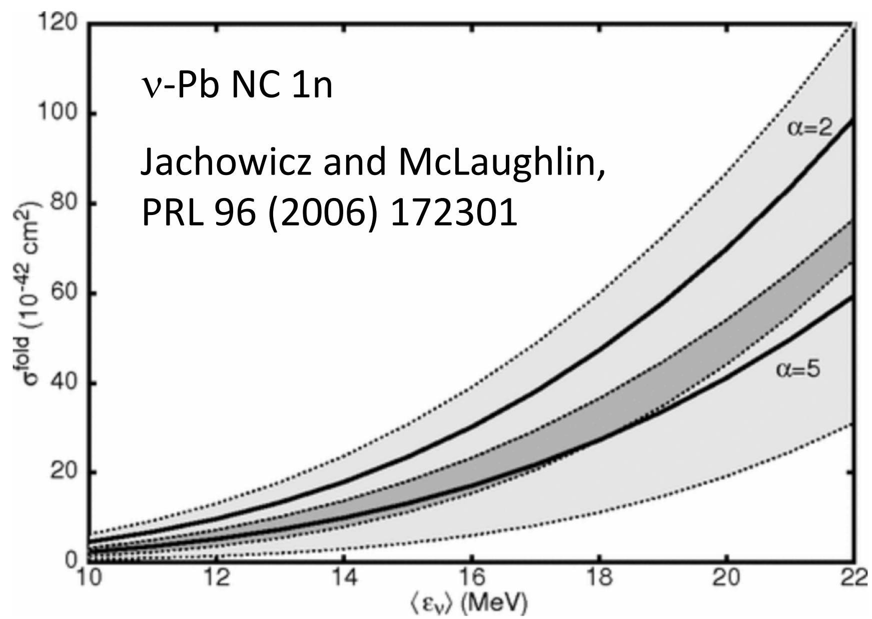
$\epsilon = 0.4, 0.6, 0.8$

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_ν> for power law spectra and different α showing the theoretical uncertainty in response

HALO-1kT Status

- have formed a new HALO-1kT Collaboration (growing – contact me!)
  - 30 some Canadians, Americans and Italians
- Many paths to obtaining 50-55% neutron capture efficiency; cost/benefit analysis of design options proceeding
- expressed an interest in the OPERA lead to the LNGS Scientific Committee; lead is being held in reserve for HALO-1kT
- made a submission to the "10 year Plan for UG Resources" exercise and submitted an LOI to LNGS
- submitting Experimental Proposal this Fall
- in contact with US DOE Isotope Program re: ^{3}He
- Preparing for ν-Pb cross section measurement at ORNL's SNS

End / Thank you