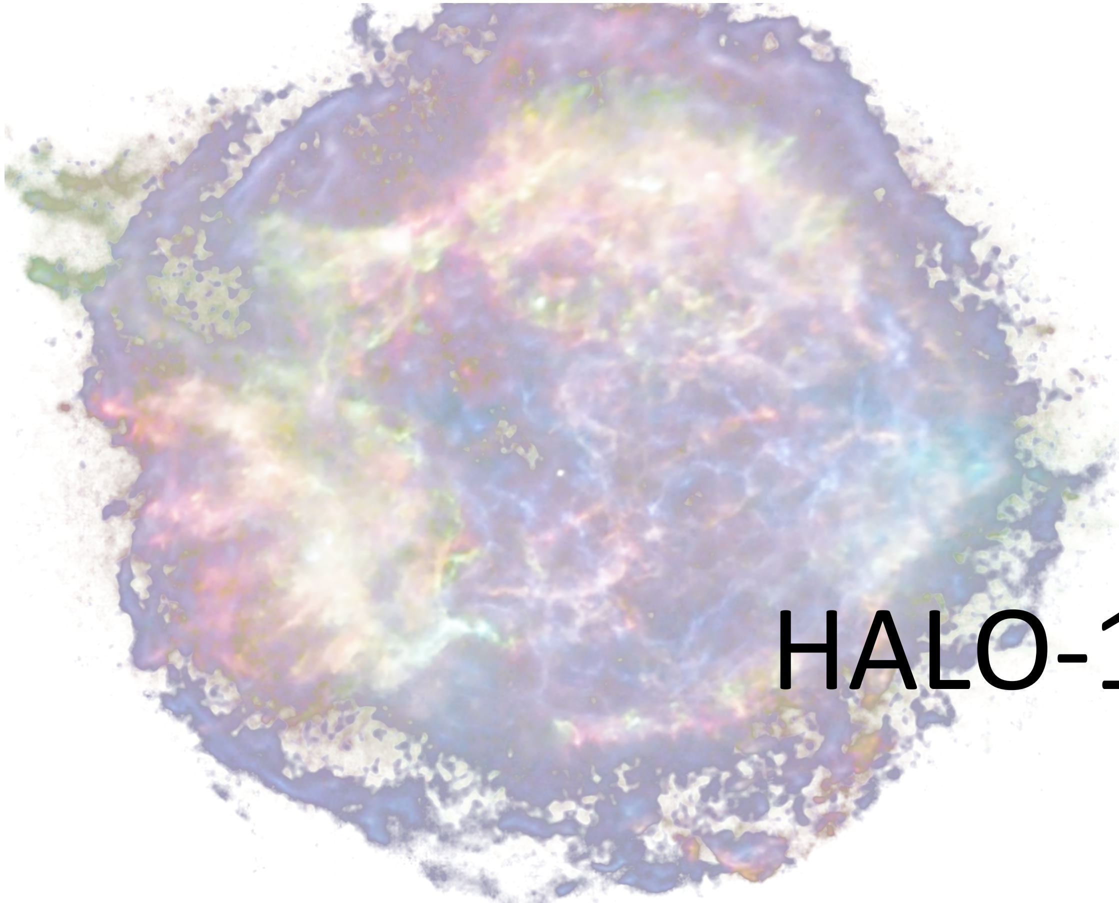


HALO-1kT

C.J. Virtue for the Collaboration

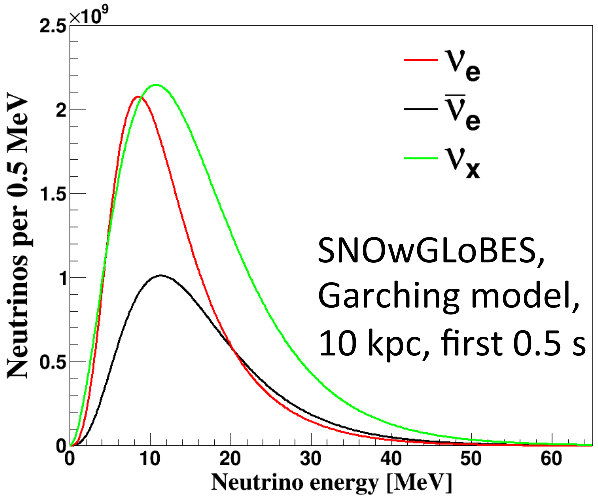
Outline

- Supernova Neutrinos
- Lead-based Neutrino Detector
- HALO
- HALO-1kT
- Risk Mitigation Strategies

- R&D details for Closed Session
- Backup slides

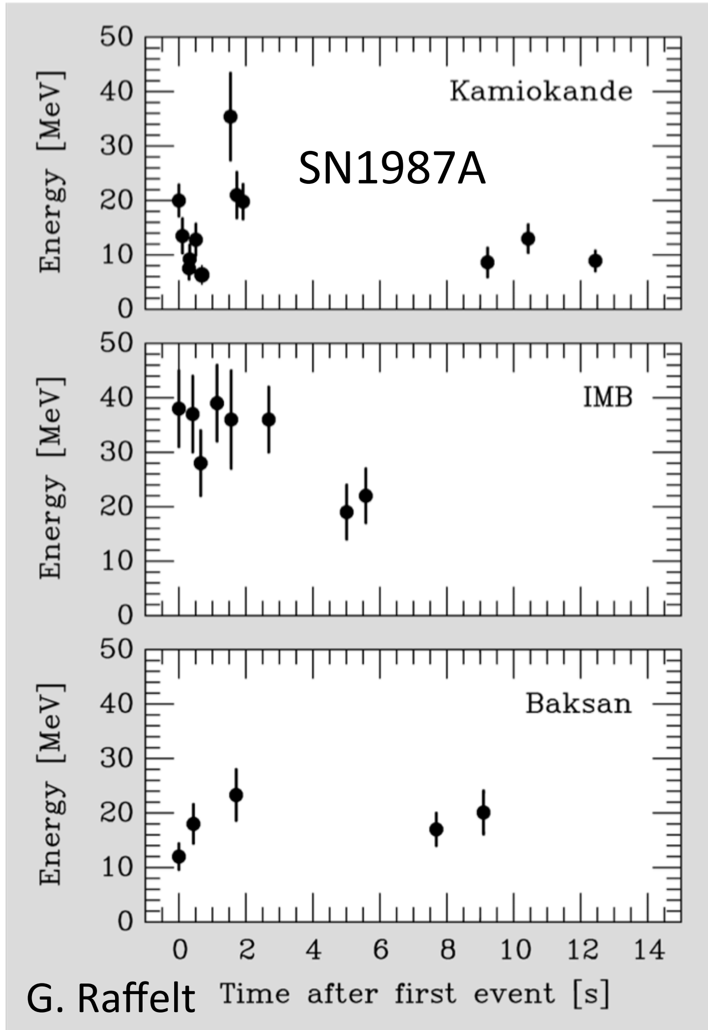
Supernova Neutrinos

- 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

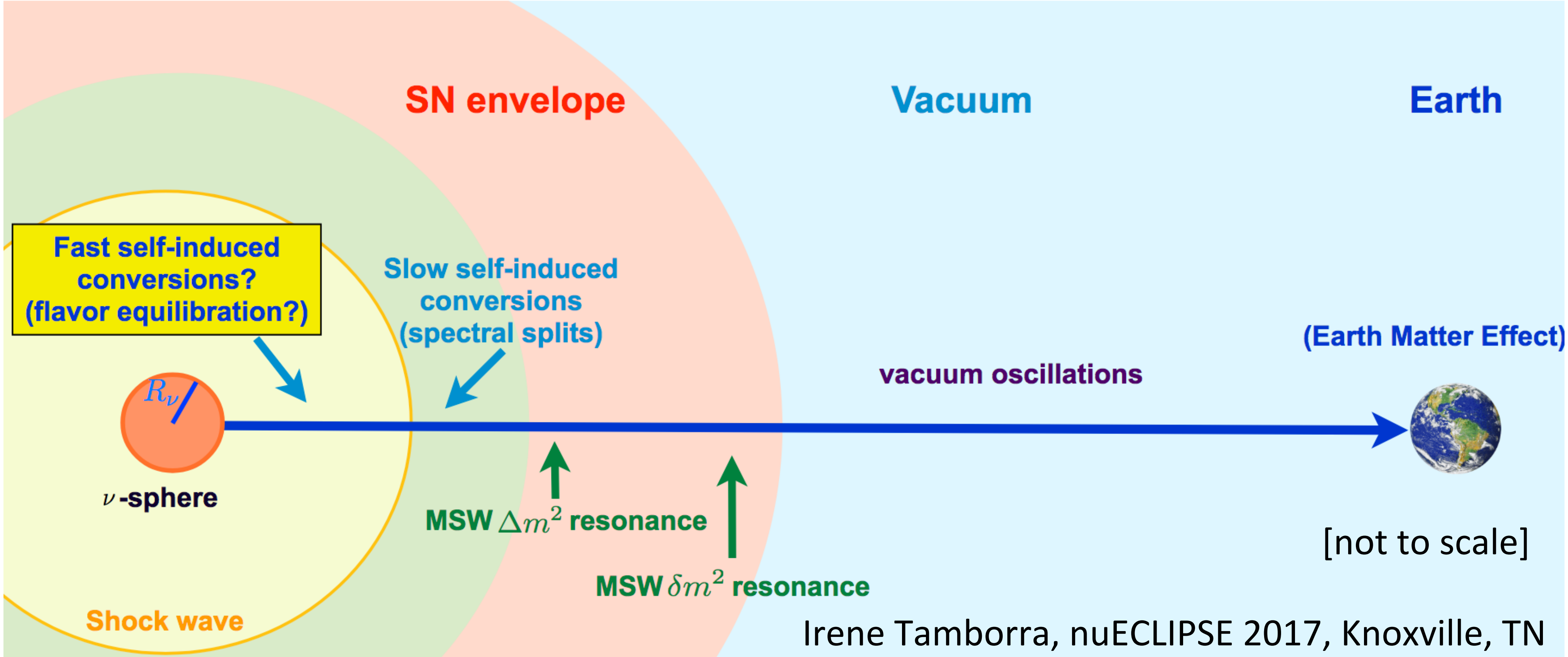


- we start with Fermi-Dirac distributions at the neutrino-spheres with:

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



Simplified Picture of Flavor 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?!

Lead-based Supernova Detector

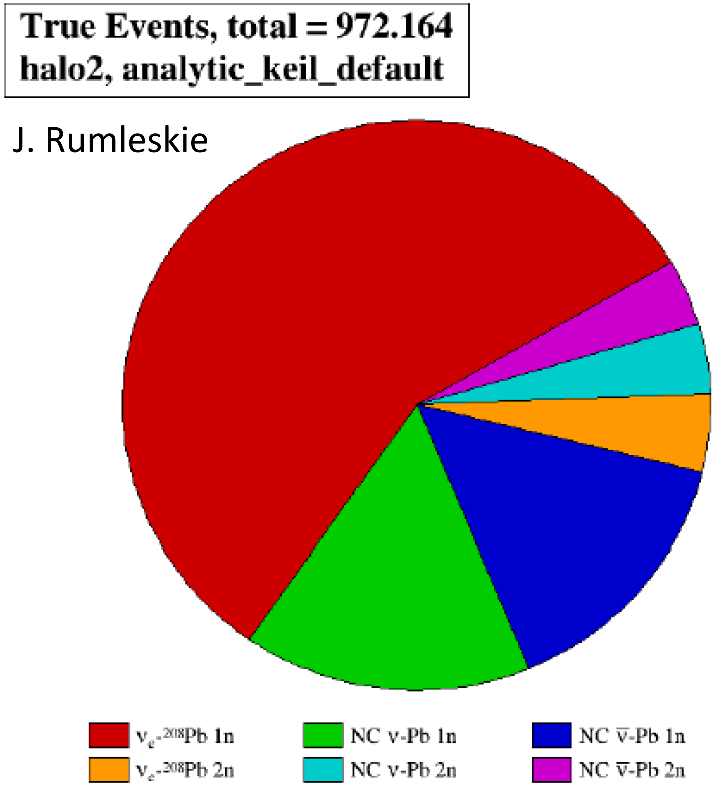
- set of detectors currently participating in SNEWS – Super-Kamiokande, LVD, Borexino, IceCube, KamLAND, Daya Bay, HALO
- with exception of HALO all are Liquid Scintillator (LS) or Water Cherenkov (WC) and are dominantly sensitive to the $\overline{\nu}_e$ flux through IBD
- lead-based SN detectors are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

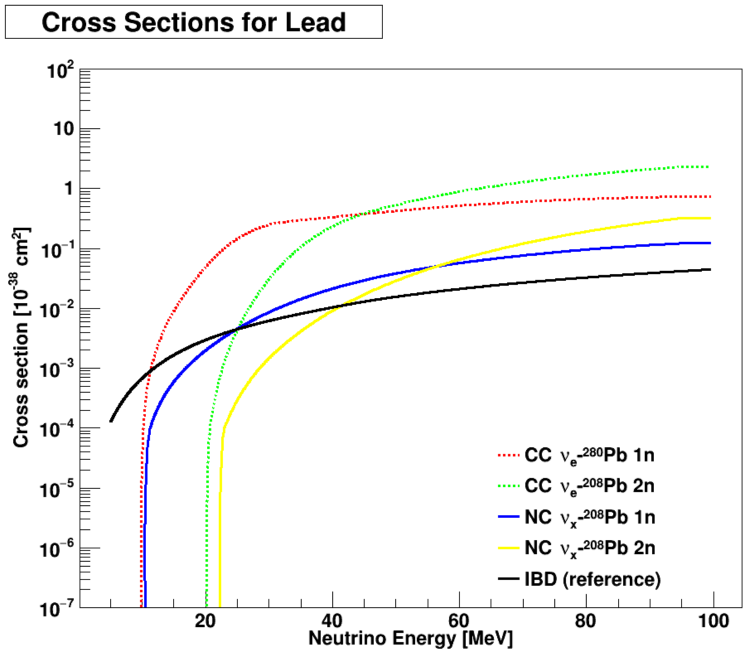
HALO / HALO-1kT Flavour Sensitivity

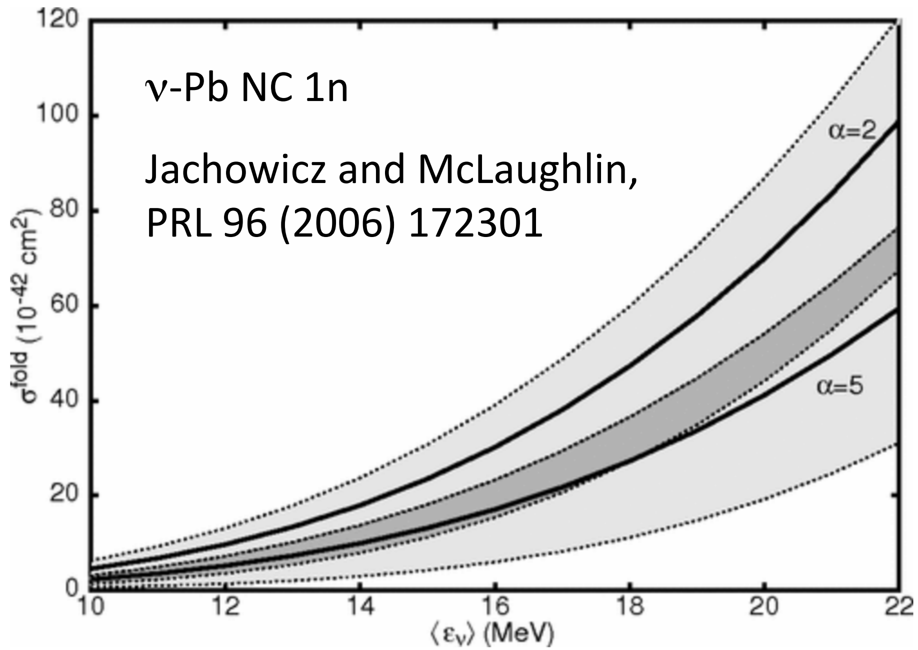
- the scientific merit of a lead-based supernova detector rests on its complementary flavour sensitivity wrt LS and WC detectors and the power that it brings to joint analyses
- the neutron excess in Pb Pauli blocks $\bar{\nu}_e$ CC reactions
- the high Z further Coulomb suppresses $\bar{\nu}_e$ CC and 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
$\langle E\nu_e \rangle$ = 15 MeV or $T\nu_e$ = 4.8 MeV
$\langle E\nu_x \rangle$ = 18 MeV or $T\nu_x$ = 5.7 MeV

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
Risk#1 – uncertainty in observed statistics for a given SN distance (mitigation later)

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:

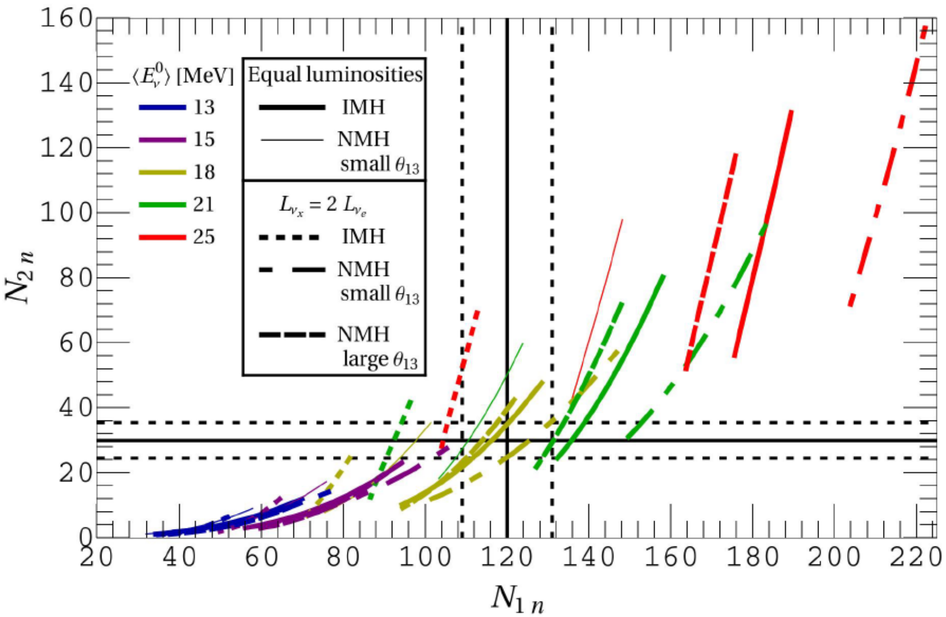
- Observation of the ν_e burst from the initial 20 ms long neutronization phase would be a signal of an inverted neutrino mass hierarchy due to the non-zero ν_e MSW survival probability of $\sin^2 \theta_{12} \sim 0.3$. Non-observation of the ν_e burst implies a normal mass hierarchy, as the ν_e survival probability is zero in this case. [Wal16].
- 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. [Dua10][Fog07]
- 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. [Fis16].

Accessible Measurements - 2

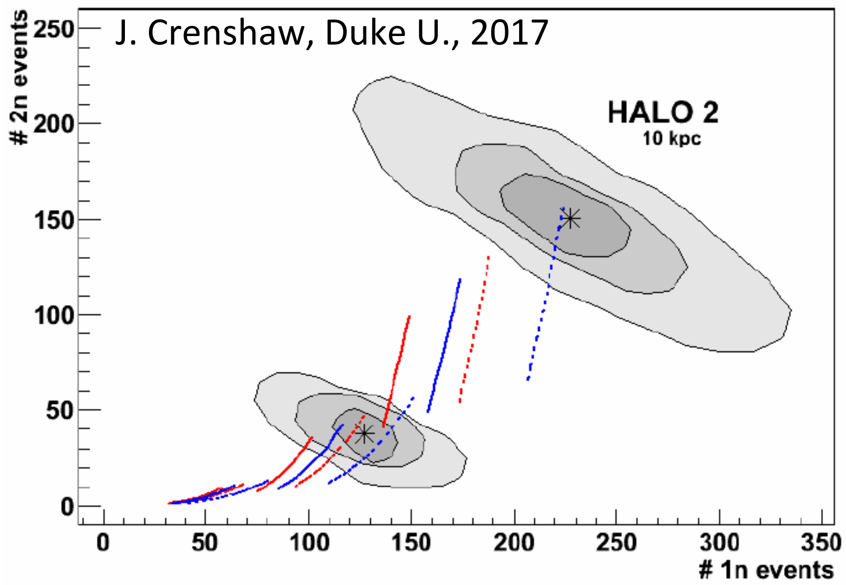
- Observation of a non-thermal neutrino spectrum or an anomalously large number of high-energy neutrinos would be an indication of the failure to trap and thermalize neutrinos in the supernova core (anomalously weak ν-nucleus interactions). [Raf11]
- Measurement of the shape (pinching) parameter of the 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 [Hor15]. 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 [Vaa11] [Sch12].
- more in LoI, references there
- Janet Rumleskie is pursuing joint HALO-1kT / SNO+ analyses

Ability to Determine $\langle E_{\nu x} \rangle$ 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



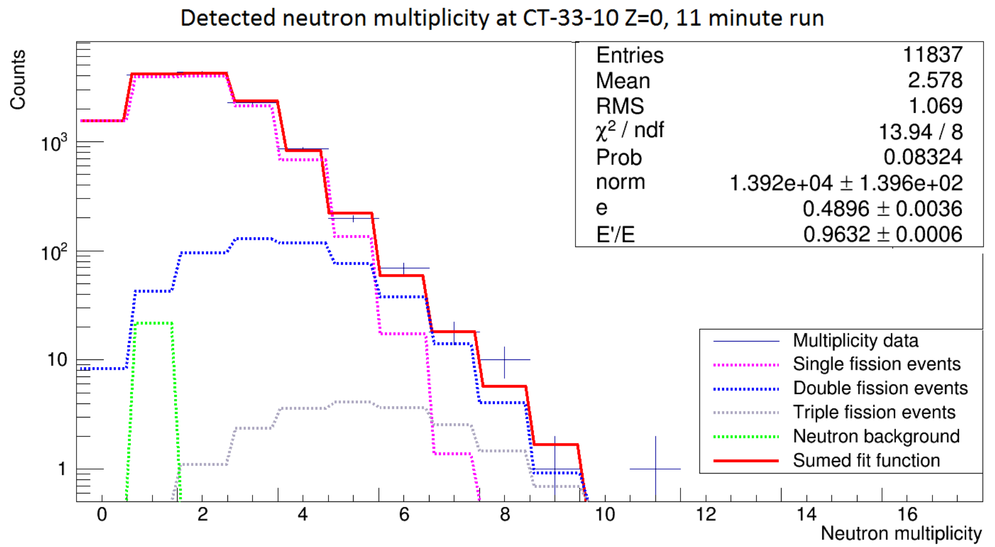
$\epsilon = 0.4, 0.6, 0.8$

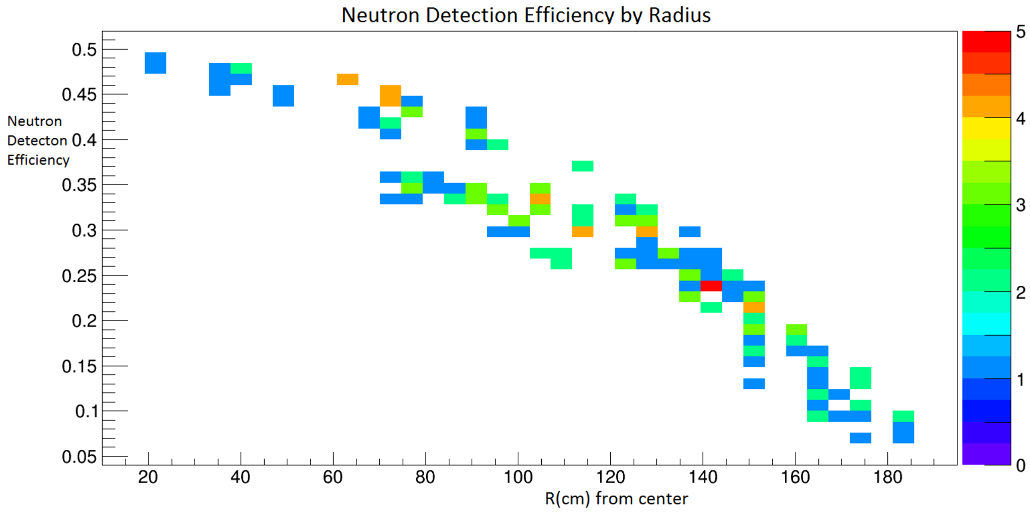
HALO at SNOLAB as a Prototype

- 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

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

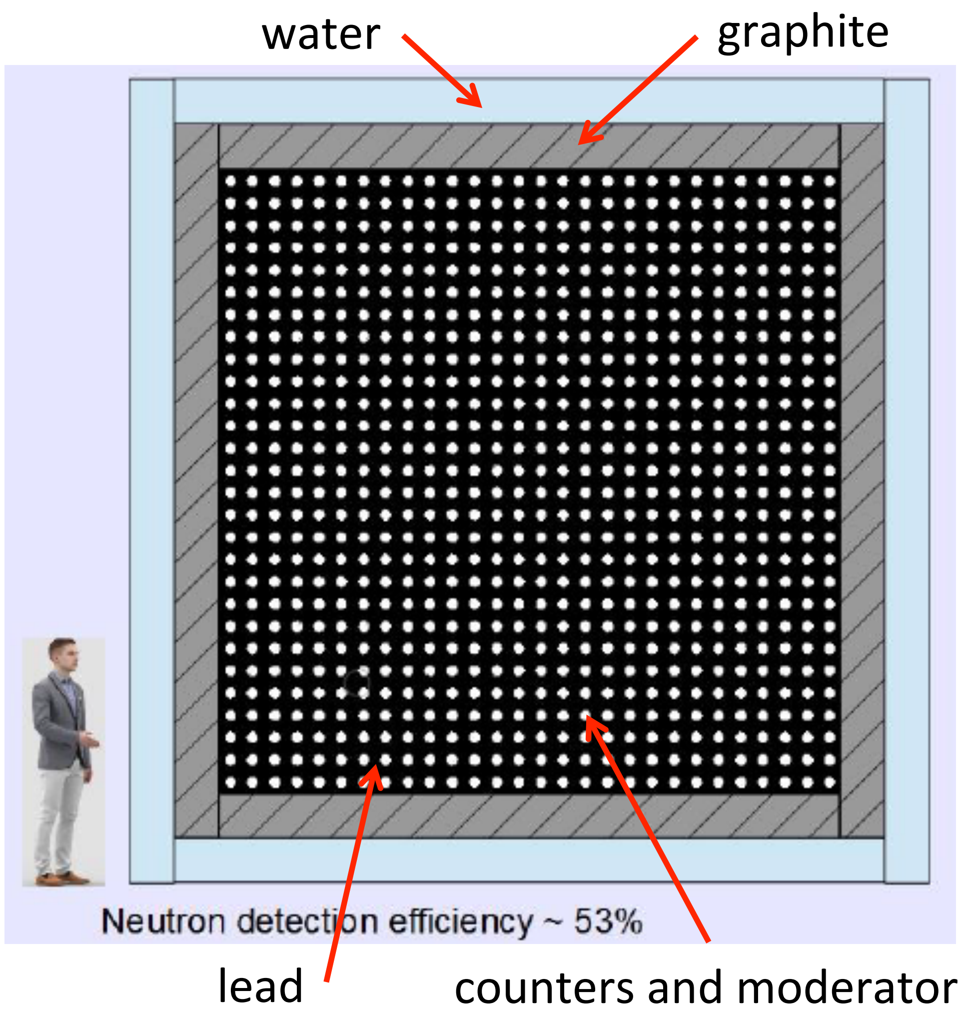
Simulation Studies

- 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 ^3He 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 ^3He – re-optimization required
  - proportional tube pressure (non-^3He component) – hints of gains to be made
- reflector and shielding require further optimization once we have conceptual mechanical design for superstructure



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

Fine / Grazie

Closed Session Slides